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RAILROAD ELECTRIFICATION

AND THE

ELECTRIC LOCOMOTIVE

OUTLINE OF PRINCIPLES INVOLVED IN RAILROAD ELECTRIFICATION.
A COMPARISON OF STEAM AND ELECTRIC LOCOMOTIVES.
HISTORY OF ELECTRIFICATION IN UNITED STATES.
DATA ON ELECTRIFICATION IN AMERICA,
EUROPE AND AUSTRALIA.

BY

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PREFACE

The importance of electrification as a method for increasing the capacity of existing steam railway facilities and reducing the cost of train operation, makes it imperative that railway officers and operating men should have some knowledge concerning the elementary theory, the design, construction, care, and operation of electric locomotives, as well as their application to all classes of railroad service.

The electric locomotive is no longer an experiment. Although in the beginning, its use on steam railroads in certain localities was practically compulsory, in order to overcome the smoke nuisance, its relation to the general transportation problem soon surpassed this state, and today, the electric locomotive stands as one of the most feasible means available for meeting the problems incident to the continually increasing traffic density as found on many American railroads. Longer and heavier trains must be handled at higher speeds and the use of electricity appears to be the logical solution of the problem.

The reliability of operation of the electric locomotive, and its flexibility of control, have been proved and the advantages that may be expected from electric operation are well known. Electric locomotives are operating successfully over a length of continuous line 440 lines long and during 24 consecutive hours a single locomotive has been able to attain a mileage of 766 miles, while the monthly mileage has reached the high figure of more than 12,000 miles. The economy in fuel consumption per unit of power delivered at the drawbar will become of increasing importance as available fuel resources decrease.

In determining the scope of this book, it has been the aim to provide, without too technical detail, information of value to anyone concerned with the operation, the maintenance

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and the repair of electric locomotives, or to anyone who in a general way is interested in the electrification of steam railroads. The fundamental units and principles of electrical science in general are explained and, in addition to descriptions and illustrations of electric locomotive design and construction, there are included examples of the practical solution of problems as encountered in the electrification of steam railway properties.

There is also appended a brief history of the electrification of steam railroads in the United States. Numerous tables are also included within this appendix, and supply valuable data covering the various electrification projects which are successfully operating in various parts of the world.

Much of the material appeared originally as a series of articles in the Railway Electrical Engineer and Railway and Locomotive Engineering. These articles, however, have been enlarged upon and rearranged.

Arthur T. Manson.

New York City.
1923

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Fig. 1—Electrified Oakpoint Classification Yard—New York, New Haven & Hartford.

RAILROAD ELECTRIFICATION

CHAPTER I

ADVANTAGES OF ELECTRIFICATION

During the past few years rapid progress in the design of the steam locomotive has taken place due to the introduction of economizing devices and superheaters. A similar advance in design has characterized the electric locomotive, however, and to-day there are single electric locomotives designed with axle loads of 65,000 lb. and with continuous capacity ratings upwards of 4,000 h.p.

Before considering the mechanical and electrical construction of the electric locomotive, it is advisable to obtain a general view of its application to railroad work; the advantages gained by its use; and its comparison with the steam locomotive as regards speed, tractive effort, horsepower rating, and operation.

Terminals.—The first application of the electric locomotive to steam railroad operation was made in terminal service, where the question was not one of economy but of civic necessity arising from the need for eliminating the nuisance and discomfort which are caused to passengers and others by the use of coal-burning steam locomotives. While at first the benefits, which were available, were not appreciated, it was not long before the many advantages of electric operation were realized and at the present time, no other method is considered practical for the operation of some terminals.

Switching.—The operating economy obtained by the use of electric locomotives is probably greater in switching service—Fig. 1—than in any other class of service. Only

one-half the number of steam locomotives are required and the saving in coal as determined by actual test has been demonstrated to be 66 per cent of the amount used by the steam engines.

Tunnels.—In some instances, a tunnel forms the throat of a railroad system. With steam operation delays are necessarily incurred while waiting for the smoke to clear, and if

Fig. 2—Hoosac Tunnel Electrification—Boston & Maine.

the tunnel is a long one, the inability to see signals presents a serious obstacle to the free operation of freight trains.

In addition to the dangers of operation and the delays incurred, there are other features very disagreeable as regards their effect upon passenger traffic. These difficulties have long been recognized by the officials of steam railroads and the advantages of electric operation in service of this class have been realized in several instances. The Hoosac Tunnel of the Boston & Maine—Fig. 2—built in 1875, is an example. Until its electrification in 1911, this point always

had been an obstruction to the traffic of this road. The delays caused by the smoke and gases made this tunnel the limited section of the division. Under steam operation the entire tunnel was a block five miles long, as no train was permitted to enter while a passenger train was passing through. By the change to electric service, maintenance costs were greatly reduced and the old troubles due to shattering of the rock and brickwork by the force of the engine exhaust, to corrosion of telephone and signal lines by acid gases, and to bad failures caused by condensing steam, have disappeared. In making repairs, track gangs can now work with safety and for a full day, while formerly only two hours of effective work in a day's shift was possible.

Among the first to realize the advantages of electrification for tunnel operation were the officials of the Grand Trunk Railway System. In 1908 they inaugurated electric service in the tunnel which connects the town of Port Huron, Michigan, with Sarnia, Ontario, and passes under the St. Clair River. The grades in the tunnel approaches, and the inclined portions of the tunnel are all 2 per cent, necessitating high tractive effort to operate the freight trains. Prior to electrification, these conditions required special locomotives, burning anthracite coal in order to reduce the smoke to a minimum. The maximum tractive effort of these steam locomotives limited the weights of trains to about 760 tons each and the speed up the grades was very slow. Since the tunnel had only a single tube and the zone system of train despatching was used, any increase in traffic prevented efficient operation. Electrification, however, not only eliminated the smoke and gases, but also increased the capacity of the tunnel about 100 per cent.

Freight Haulage.—A new opportunity has recently developed for the use of electric locomotives, namely, hauling of freight over the heavy grades of mountain divisions. The railroads derive practically 70 per cent of their total revenue from the transportation of freight so that economy effected in this service has a favorable bearing on total net revenue.

Advantages.—Two important characteristics of the electric locomotive have been demonstrated conclusively.

First.—Complete reliability is obtained under all conditions

FIG. 3—The Necessary Fuel Consumption Is a Source of Stand-by Losses at Steam Railroad Terminals Which Serve Suburban Commuting Service.

of service. The power of full capacity is available in either warm or freezing weather. In cold weather, the excessive heat radiation which is disastrous to the steam engine, is of benefit to the electric locomotive, as more current can be passed through the motors without over-heating and their capacity is, therefore, increased. Moreover, the services of electric locomotives are available at all times, since detentions are not necessary to clean boilers and grates, to take water, or to light or to bank fires. Under steam operation only 30 per cent to 40 per cent of the total locomotive hours are spent on the road, whereas with the electric locomotives over 90 per cent of each 24 hours may be given in service. Greater mileages can be made between the periods when running repairs and inspections must be made. Stand-by losses—Fig. 3—common to steam locomotives are eliminated.

Second.—The maintenance cost is low as compared with the steam locomotive. The maintenance of electric locomotives will average about 65 per cent of that of steam locomotives of equal weight. This is apparent when we consider that at least one-half of the costs of repairs of the steam locomotive is expended on the boiler.

In general, the electric locomotive has characteristics which are especially advantageous to railroad operation, namely:

1—Track capacity can be increased by 100 per cent in certain instances. Stops for coal and water are eliminated and increased schedule speed results.

2—A flexibility of operation is possible which permits two or more units to be coupled together and handled by a single crew.

3—A symmetrical wheel arrangement permits of operation in either direction.

4—Operation is simple—all the electrical apparatus is so arranged that by the movement of small handles the power is connected to the motors and the locomotive is brought up to speed.

5—Operation is from the front end, where the engineman's vision is unobstructed and the best possible view of the track is obtained.

The reliability and freedom from failure of the electrified

service in and about the City of New York is noteworthy. Here are located the electrified operating terminals of the two greatest railroad systems of the world, the train service on both of which statistics show to be less subject to interruptions and delays since operated by electricity than under the best results ever obtained when steam locomotives were used.

There is no longer a question of whether electricity can do the work of broadening, extending, and improving the very admirable performance of the modern steam locomotive. This has been amply demonstrated.

The trend towards electrification is due not alone to the many inherent advantages of the electric locomotives, but to other important reasons. The rise in the cost of fuel greatly has increased the operating costs of steam locomotives. Electric power can be produced at a low cost due to the development in hydro-electric and steam generating plants. As the growth of traffic in the United States continues to increase, the facilities necessary for the movement of this traffic will have to be increased. When this point is reached the high cost of adding to the number of tracks will make it necessary to increase the service over the present tracks, and this end can be accomplished most readily with electric operation.

CHAPTER II

ELECTRICAL TERMS AND THEIR RELATION TO MECHANICS

Although the actual nature of electricity itself is still unknown, a general knowledge of electrical phenomena has become common and some conception concerning the meaning of the electrical units, such as the volt, the ampere and the watt is also general, although use is often made of these words and other electrical terms, without understanding fully what they actually mean and for what they stand. The purpose of this chapter is to explain the meaning of some of the electrical terms, and to show the relation between them.

Electricity.—Electricity is the name given to an invisible agent which is regarded as the cause of certain chemical and physical phenomena. Although many of the effects produced, now are understood well, little is known as yet of the precise nature of electricity itself. It is not matter, nor is it energy alone; yet it can be combined with matter, and energy can be expended to create and move it. A fact of greatest importance is that the energy spent in generating electricity in one part of a system can be transformed into heat, or light, or work at some other part of the system, and this transfer of energy may take place although great distances intervene. In the usual conception, electricity is often associated with lights, or with power, or something which is flowing through conducting wires. There are, however, several forms of electrical energy, including what is known as static electricity and also magnetism—these two forms of electrical phenomena having been known long before current or dynamic electricity.

Static Electricity.—Static electricity can be produced by friction and remains upon the surface of bodies. If a glass is rubbed with a piece of silk or flannel, it will be found to have acquired a property which it did not previously possess,

namely, the power of attracting to itself pieces of paper, light bodies, dust, etc. When in this condition, the glass is said to be charged with static electricity. The same condition exists if a stick of sealing wax is rubbed with flannel, woolen cloth, or fur. The quantity of electricity produced by friction is spoken of as a charge, and a body when electrified, is said to be charged. When the electricity is removed it is said to be discharged.

Conductors and Insulators.—Certain materials are better suited than others, for the passage of electric currents. To those bodies which allow electricity to flow readily through them or rather over their surfaces, the term conductors is given. To those bodies which oppose with great resistance, the conduct of electricity, the term insulators is given. All of the metals are conductors, some being better than others. The human body is a conductor and so also is water. On the other hand, oil, glass, silk, shellac, mica, rubber, porcelain, micarta, etc., are insulators. These substances are therefore used for supporting or separating electrical apparatus and wires which carry electricity.

The Magnet.—The ancients gave the name magnet to certain hard, black stones, which possessed the property of attracting small pieces of iron. These stones were natural magnets or lodestones. It was later found that artificial magnets could be made from these natural ones. If a piece of iron was rubbed with one of these lodestones, it would acquire the same magnetic characteristics as the stone itself, and would attract small pieces of iron, and if hung on a thread, it would point north and south. It was found that there were two opposite kinds of magnetic poles; one was called the north pole and the other, the south pole. Between these two poles, it was discovered, there existed invisible "lines of force" forming what is known as a magnetic field. Later experiments proved that the magnet and magnetic field could be produced by winding a coil of wire around an iron center and passing electricity through the wire. This is the method used to produce the field in the electric generators and motors of today.

Current Electricity.—Certain materials have been described as being conductors of electricity and others as non-conduc-

tors or insulators. The charge of static electricity on a body will be removed or decreased if a conductor is connected between the body and the ground or another body having a weaker charge. If by any arrangement, electricity could be supplied to the body as fast as it flowed away, a continuous current would be produced; that is, if the ends of the conductor were kept at different electric pressures or voltages. The manner is similar to that of the current of heat which will flow through a metal rod if the ends are kept at different temperatures, the flow being always from the higher temperature to the lower.

The Volt.—Electricity flowing in a wire is analogous to water flowing in a pipe. In water pipes a difference of level produces a difference in pressure, which will cause a tendency for the water to flow from the high level to the low level. So it is with electricity. A difference of potential produces an electro-motive-force or voltage and the voltage sets up a current as soon as the circuit is closed. In the pipe there are a certain number of units—cubic inches—which are flowing at a certain rate per minute, and these units are under a certain pressure measured in pounds per square inch. In the wire carrying electricity, there is the unit of electricity, the ampere; the unit of quantity, the coulomb; and the unit of pressure, the volt. Increasing the pressure in the pipe increases the flow of water, so also increasing the voltage increases the current or amperes. The amount of water flowing depends also on the size of the pipe and the capacity of the reservoir. With a small pipe, offering high resistance, the amount of water will be much less than with a larger pipe of lower resistance. With electricity, the amount passing through depends on the voltage, on the resistance of the conductor and capacity of the generator. With a constant pressure the quantity of electricity will be directly proportional to the resistance.

There is, however, a standard which determines directly the value of the volt, namely, the Clark Standard Cell. When its temperature is 15 degrees Centigrade, the voltage of this cell is 1.434 volts.

The Ohm.—The ohm is the unit of resistance. All substances offer some resistance to the passage of electricity

through them, the strength depending on the substance itself, on its length, and on its cross-section. The analogy between electricity and the water in a pipe will help again. As long as the pressure remains constant, the amount of water which flows, depends upon the resistance of the pipe. If the pipe is small, long, and full of bends, the water will run slowly through, whereas if it is straight and of short length the resistance to the flow will be less. If the metal wire is very small and of considerable length, only a very feeble current may flow even when considerable voltage or pressure has been applied, the resistance being different with different metals. Copper is of very low resistance, while iron is of relatively high resistance. The resistances of all metals increase with an increase in temperature, while carbon and solutions which are conductors, decrease in resistance when an increase in temperature occurs.

The international ohm is defined in terms of the resistance of a column of mercury. To be exact, one ohm is the resistance of a uniform column of mercury 106.3 centimeters long and 14.4521 grammes in mass at 0 degrees Centigrade. A conductor has a resistance of one ohm when the pressure required to send one ampere through it is one volt.

The Ampere.—The ampere is the unit of electric current and is defined in terms of the amount of silver which is deposited when electricity is passed through a nitrate of silver solution. To be exact, it is the amount of current which will deposit silver at the rate of 0.001118 of a gram per second, when flowing through a solution made up of 15 parts by weight of a neutral solution of silver nitrate and 85 parts of water.

The ampere, the ohm and the volt bear a certain relation to one another. The volt is the pressure which will drive one ampere through a resistance of one ohm.

The Watt.—The power available from the water in the pipe is equal to the product of the amount and the pressure; so similarly, with electricity, the power available in a circuit is equal to the volts multiplied by the number of amperes. This unit of power is called the watt. One ampere at one volt equals one watt. For instance, if we have 100 amperes at 10 volts, the power will be 10 x 100=1,000 watts, or one kilowatt. (*Kilo* is a Greek word, and means one thousand.) There

would still be the same power if 10 amperes at 100 volts were flowing, as the same product—1,000—is obtained. If this current should flow for three hours the energy consumed would be three kilowatt hours.

Electricity by Chemical Action.—It may further be explained that electricity is related to chemistry and can be generated by means of chemical action. Take, for instance, the so-called voltaic pile and the various cells. The voltaic pile is made by placing a pair of discs—one of zinc and one of copper—in contact with each other, then laying on the copper disc a piece of flannel or blotting paper moistened with brine, after which a similar pair of discs are placed in position and so on through the series, each pair of discs in the pile being separated by a moist conductor.

Battery cells are made by placing two metals in a weak acid solution, as in the case of zinc and copper in a solution of sulphuric acid, or zinc and carbon in a solution of salammoniac.

It is also possible to produce chemical action by the passage of a current of electricity through certain solutions. When electricity is passed through a solution of sulphate of copper or "blue vitriol," as it is commonly called, the solution is broken up, and metallic copper is deposited on one of the terminals in the solution. The amount of copper deposited is proportional to the amount of current passing through. One of the early types of electric meters for house circuits was based on this principle. The current consumed by the lights was passed through such a solution and the amount of the deposit in ounces was determined by weighing the proper terminal every month. From the increase in weight the amount of current became known and the consumer was charged accordingly.

Relation to Mechanics.—The volt has been referred to as the electrical unit of pressure and the value has been defined in terms of the Clark Standard Cell. The term pressure also conveys a certain definite meaning when considered from a purely mechanical standpoint, and the question arises at once, as to the relation between the electrical and mechanical units. Does the volt approximate the grain, the ounce, or the pound? On first thought, the volt appears as an electrical unit not a

mechanical one, and therefore it appears as if no comparison could be drawn.

If, however, the means of obtaining pressure, or of setting matter in motion, is considered separately from the resulting pressure or motion, a proper comprehension can be obtained, since the laws of pressure or force constitute the science of mechanics and cover all the phenomena of force as applied to matter, whether at rest or in motion. All questions of force, therefore, can and must be viewed accordingly. While the cause of pressure or motion may be electrical, the resulting force is mechanical, and although we may not know what electricity in itself really is, still we may have a clear knowledge of the results it produces.

Centimeter - Gramme - Second System - The Dyne. — The whole system of electrical calculations as related to mechanics is based upon the centimeter-gramme-second system; the unit of length or space is the centimeter, the unit of mass, and practically of weight, is the gramme, and the unit of time is the second. This is referred to as the c. g. s. system.

The force required to move a mass of one gramme at a velocity of one centimeter per second, after having been applied for one second, is called the unit of force and is known as the dyne. It will be noticed that this is a purely mechanical definition and therefore is in keeping with the mechanical system of units, based upon the force of gravity and the laws of falling bodies.

The force of gravity varies slightly at different locations on the earth's surface, depending on the latitude, but for all practical purposes a constant, 32.2, can be used. That is, the action of gravitation is such that a falling body will in one second reach a speed of 32.2 ft. per second, or for a given number of seconds the speed will be a corresponding multiple of this speed. Here the pound is considered as the unit of mass, and the unit of distance as the foot. If the relations between the gramme and the pound, and between the centimeter and the foot are known, the laws of gravity can be expressed in terms of the dyne, and thus show the relation to the electrical units which, as previously stated, is based on the dyne.

One pound avoirdupois is equal approximately to 453.6

grammes and 32.2 feet is equal approximately to 981 centimeters. The force with which a body gravitates, i.e., the force with which the earth attracts any mass and usually called the weight of the mass, is equal to the mass multiplied by g or in terms of the c. g. s. system, one pound of force is equal to 453.6 x 981 = 444,982 dynes.

Mechanical Equivalents.—As previously stated, the volt is the force which causes one ampere to flow through a resistance of one ohm. The volt can be and is expressed in terms of the dyne; it is equivalent to 10^8 or 100,000,000 dynes.

In a preceding paragraph it has been established that a force of one pound is equal to 444,982 dynes, so that dividing the value of the volt in dynes by the number of dynes equivalent to a pound, the value of the volt can be expressed in pounds and is equivalent to $\frac{100,000,000}{444,982} = 224.73$ lb.

The unit of resistance is also expressed in dynes and is 10^9, so that the ohm is equal to 2,247.3 lb.

These magnitudes are so much greater than the general conception of the value of the corresponding units that a further comparison will be made. It is known that electricity is closely related to heat and that current flowing through a conductor will generate heat. It is also known that, by vibration, or by moving of the particles, heat can be produced in metals. For instance, a wire, when bent rapidly back and forth, generates heat, due to the movement of the particles of the wire against the force of cohesion. If the theory that electricity acts similarly on the molecules, is accepted, then the reason for the heating and the magnitude of the unit of the force, or volt, as shown in the preceding paragraph, are apparent.

The unit of work is the work done in overcoming unit force through unit distance. In the c. g. s. system it is the work done in overcoming a force of one dyne through a distance of one centimeter. This unit of work is called the erg.

Power is the rate at which work is being done. It may be expressed in foot-pounds per second, or in ergs per second.

The watt, expressed as 10^7 ergs per second, is analogous to the foot-pound, in that each is a unit of pressure or weight acting through a unit of space, and in neither case is the ele-

ment of time introduced; that is, a watt of work will be the same amount no matter how long it may take to do it, exactly as a foot-pound is equal to one pound lifted one foot high without reference to the time required. If, however, the time of performing these amounts of work is limited to the unit of time, that is, to one second, the former case becomes one watt-second, or one "joule," which is a rate of doing work, or "power." There is no specific name for the foot-pound lifted in one second, but there is the term horsepower, which is 550 foot-pounds per second.

A comparison may now be instituted between the watt and the horsepower. One foot equals 30.48 centimeters and the force of one pound we have seen equals 444,982 dynes, so that one horsepower is represented by $30.48 \times 444{,}982 \times 550 = 7{,}460{,}000{,}000$ ergs per second. Since one watt is equal to 10^7 ergs per second, one horsepower is equal to 746 watts.

CHAPTER III

OHM'S LAW—SERIES AND PARALLEL CIRCUITS

In the preceding chapter has been shown the relation between the volt, the ampere, and the ohm. The voltage or force tending to move the electricity is designated by "E"; the rate of flow or current is designated by "I," and the resistance which the force must overcome to produce the flow of electricity is designated by "R." The relation existing between these three factors was discovered and expressed by Ohm, and is known as Ohm's law of electrical resistance. The law is as follows:

"The current in a circuit is directly proportional to the electromotive force, E, and inversely proportional to the resistance, R." The law also may be written in the form of an equation, thus, $I = \frac{E}{R}$, that is, if the electromotive force E, be increased, the current will be increased in the same proportion; if the resistance, R, be increased the current will be decreased proportionally. Likewise a decrease in the resistance, R, causes a proportional increase in the current.

Simple Circuit.—There are three factors involved in this equation, so that if any two of these factors are known the third can be determined. The following examples illustrate this point:

Examples:—

1. If 110 volts is applied to a circuit having a resistance of 20 ohms, how much electricity will flow?

Ans. $I = \frac{E}{R}$, $I = \frac{110}{20} = 5.5$ amperes.

2. What voltage would be necessary in order to force a

current of 23 amperes through a resistance of 340 ohms?

Ans. $I = \frac{E}{R}$; or $E = I\,R$; or $E = 23 \times 340 = 7820$ volts.

3. If it is desired to obtain 7.5 amperes and the source of power is 110 volts, how much resistance will be necessary.

Ans. $I = \frac{E}{R}$; or $R = \frac{E}{I}$; or $R = \frac{110}{7.5} = 14.67$ ohms.

Series Circuit.—The above examples illustrate problems encountered when dealing with a simple circuit, but the same principle or law applies to any direct current circuit.

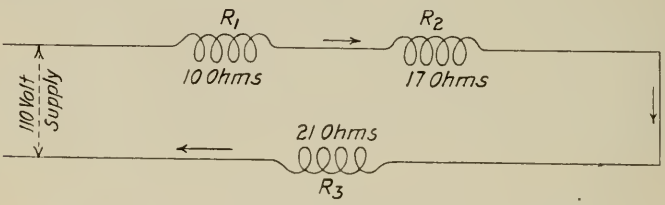

Fig. 4—Illustration of a Circuit Containing Resistances Connected in Series.

Both series and parallel circuits are encountered in electrical work, and it often becomes necessary to determine throughout the circuit, the electricity flowing or perhaps to make an analysis of the voltage-drop. In the series circuit the several parts are joined together in such a manner that the current passes through all the parts, one after the other, as in Fig. 4. The total resistance is, in this case, the sum of the separate resistances, and this total resistance must be obtained in order to determine the amount of current, as in the following example:

4. Referring to the circuit having three coils of 10, 17 and 21 ohms, respectively, in series—Fig. 4—across 110 volts, how much electricity is flowing? The calculation follows:

$$I = \frac{E}{R};\ I = \frac{E}{R_1+R_2+R_3};\ I = \frac{110}{10+17+21} = \frac{110}{48} = 2.292 \text{ amps.}$$

5. In a circuit of 9 arc lamps in series, each lamp has a resistance of 5 ohms, and a current of 3.7 amperes is required to give the proper light. What voltage must be applied?

Ans. $I = \frac{E}{R}$; $E = I\,R$; $E = 3.7\ (9 \times 5) = 3.7 \times 45 = 166.5$ volts

At times it is necessary to know the voltage-drop across any

or each of the various parts which go to make up a circuit. For instance, referring to Fig. 4, it might be interesting to know what voltage drop exists across each of the three resistances. In this particular problem we know from Example 4 that 2.292 amperes is flowing. Since Ohm's law can be applied to any part of a circuit, the voltage-drop across each of the coils is then $E = IR$, and is as follows:

$E = 2.292 \times 10 = 22.92$ volts drop across the 10-ohm coil.
$E = 2.292 \times 17 = 38.96$ volts drop across the 17-ohm coil.
$E = 2.292 \times 21 = 48.13$ volts drop across the 21-ohm coil.

Parallel Circuits.—An illustration of parallel or divided circuits is shown by Fig. 5. The current on reaching point "a" divides, a certain amount passing through r_1 and the rest

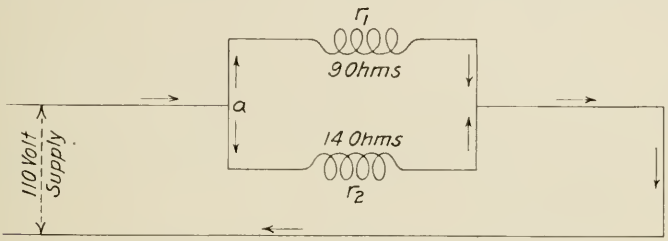

Fig. 5—Arrangement of Circuit with Resistances in Parallel.

through r_2. The problem is to determine how much current passes through each branch. The amounts depend upon the relative resistance of the two circuits, the one with the lower resistance taking the greater amount of current.

If both circuits were equal in resistance, the currents in each would be equal. If the resistance of one be twice that of the other, then one-half will flow through the first and double the half, or one will flow through the second. In other words, the amount of current would depend upon the ability of the circuit to carry the current or upon its "conductance." Conductance may be said to be the inverse of resistance; in fact, it is the reciprocal of resistance. It may be defined as equal to $\frac{1}{R}$, and therefore becomes greater as the resistance decreases. For example, if the resistance of a circuit is 2 ohms the conductance is ½. If the resistance is ¼ ohm the conductance is 4.

In the case of the circuit in Fig. 5, the resistances are r_1 and r_2, so that the conductances are $\frac{1}{r_1}$ and $\frac{1}{r_2}$.

It is obvious that the joint resistance of these two parallel circuits is less than the resistance of either one. Now if we let R represent the joint resistance, then $\frac{1}{R}$ represents the joint conductance, and this joint conductance will, of course, equal the sum of the two conductances. We have then

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} = \frac{r_1 + r_2}{r_1 r_2}; \quad R = \frac{r_1 r_2}{r_2 + r_1}$$

This formula for the resistance of parallel circuits having two divisions can be put into the shape of a rule as follows: "The joint resistance of a divided circuit of two divisions is equal to the quotient obtained when the product of the separate resistances is divided by their sum."

What is the joint resistance of the circuits in Fig. 5; also how much electricity will flow from the source of supply, and how will it divide?

$$R = \frac{r_1 r_2}{r_1 + r_2} = \frac{9 \times 14}{9 + 14} = \frac{126}{23} = 5.48 \text{ ohms.}$$

The total current will then be $I = \frac{E}{R} = \frac{110}{5.48} = 20.07$ amps.

This current will divide in the ratio of 9 to 14, that is, $\frac{14}{23}$ will go through r_1 or 12.21 amperes and $\frac{9}{23}$ will go through r_2 or 7.86 amperes.

If there are more than two divisions, a similar rule is followed. Suppose, for instance, there are three circuits, r_1, r_2, r_3:

Then

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} = \frac{r_2 r_3 + r_1 r_3 + r_1 r_2}{r_1 r_2 r_3};$$

and

$$R = \frac{r_1 r_2 r_3}{r_2 r_3 + r_1 r_3 + r_1 r_2}$$

CHAPTER IV

INDUCTANCE AND CAPACITY

In the two preceding chapters have been explained the meaning of several electrical terms, such as the ampere, the volt, the ohm, and the watt. Ohm's law has been explained and examples chosen to illustrate the use of this law. The relation of the electrical units to mechanics has also been pointed out. There are two other important factors which should be considered, namely, inductance and capacity.

Discoveries of Faraday.—As early as 1831, Faraday discovered that currents could be induced in a closed circuit by means of magnets, these magnets being moved close to the circuit, and that similar currents could be induced if a coil or closed circuit was moved across a magnetic field. Continuing further, after this discovery, he found that a current whose strength was changing, i.e., either increasing or decreasing, would induce a secondary current in a closed circuit near to it. Such currents, whether generated by a magnet or by other currents, are known as "Induction Currents." The modern electric generators, induction coils, transformers, and other similar appliances are based upon this principle.

Since induction plays such an important part in the electric field, these discoveries of Faraday should be explained in some detail, so that the principles will become entirely familiar to the reader and so that the principles of the transformer, generator, etc., may be better understood when discussed in later chapters.

Take, for instance, the example of a spool on which are wound a large number of turns of insulated wire, the two ends of which are connected to an electrical measuring instrument for indicating when electric current is induced in the wire and the direction of this current. If the north pole of a bar mag-

net is inserted inside of the spool, a momentary current is observed to flow while insertion is taking place. When the bar magnet is held stationary no current is induced, and when the magnet is withdrawn the induced current flows in the opposite direction. The magnet does not grow any weaker by being so used, for the real source of the electrical energy generated is the mechanical energy spent in moving the magnet in and out of the coil. If the ends of the wire are not connected, and the coil is open-circuited, no currents are produced. However, an electro-magnetic force or a voltage tending to produce a current, will be set up.

As another illustration, take two coils of wire, adjacent to each other, with the centers on the same axis. In series with the first coil and a source of electrical energy assume a telegraph key so that when the key is closed electricity will flow through the coil. This coil will be called the primary coil. Also assume the other coil, which will be called the secondary coil, connected to the electrical instrument for measuring current. It has been found that whenever electricity is allowed to flow in the primary coil, a current will be induced in the secondary coil, but this current will only be induced momentarily while the current in the primary coil is increasing from zero to its maximum value. When the circuit to the primary coil is broken, current is again induced in the other coil, but only while the current is decreasing from maximum to zero. So long as a steady current traverses the primary circuit, no currents are induced in the secondary circuit.

Induction Due to Alternating Current.—Induction and induced current are generally associated with alternating current, and are not necessarily considered in connection with direct current. The reason for this is obvious. Direct current has a practically constant value, and as we have just seen, secondary currents are not induced when the primary current is constant. Alternating currents are not constant in value, but change rapidly from a maximum to zero, to a negative maximum, and back to zero, this cycle taking place in a fraction of a second. In the case of a 60-cycle current there are 60 of these cycles per second.

It has been explained how induced currents occur whenever the current changes in strength and the amount of the induced

current depends on the rapidity of the rate of change. A good deal of inductance should therefore be expected when the current through circuits of various kinds is alternating. And this is so. Inductance is an important factor when dealing with alternating current and proper allowance must be made for it, as well as the resistance of the circuit. In some cases, the inductance of a circuit may be greater than its ohmic resistance.

The Transformer.—This same principle of induction applies to the transformer. A simple transformer is shown in Fig. 6, and consists of an iron ring, I, on which are wound two sets of

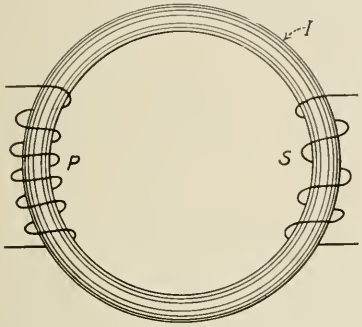

Fig. 6—Arrangement of Parts for a Simple Transformer.

turns, P and S. When the current is interrupted, say in the turns, P, a current of electricity at a certain voltage is induced in turns of wire, S. The making and breaking of the current in the turns, P, causes a change in the number of lines of force, surrounding them, and this change induces, in the iron ring, a magnetic flux (or lines of force). This magnetic flux cuts the wires, S, and a current is induced in them.

The function of the transformer is to transform electrical energy at one voltage to electrical energy at another voltage. The ratio of the electrical voltages between the two sets of coils is equal to the direct ratio of the number of turns of wire in each coil. For instance, if there were 10 turns in coil, P, and 5 turns in coil, S,—Fig. 6— and if alternating current at 220 volts was connected to the terminals of the coil, P, then the voltage across the terminals of coil, S, would be in the ratio of 10 : 5 or equal to 110 volts.

Electrical power is represented by kilowatts, or the product of volts and amperes. It has been shown that voltage can be changed from 220 to 110. Under the same circumstances,

what does the current do? Does it reduce one-half, does it remain the same, or does it double? If there were no losses in the transformer, i.e., if the transformer were 100 per cent efficient, the current would have to double when the voltage was transformed to one-half in order to keep the input and output the same. No machine or apparatus, however, is of 100 per cent efficiency, but the transformer, having no rotating machinery or moving parts, is of high efficiency, approximating 98 per cent. In the case, therefore, of the transformer with ratio of 10 turns to 5 turns, if 100 amperes were flowing into the 10 turns, P, the current strength in the 5 turns, S, would be slightly less than 200 amperes.

Large numbers of transformers are used to reduce the high-voltage of a supply of energy, to low-voltage energy that is safer and more convenient for operating lamps, motors, and other devices. Transformers used for this purpose are called "step-down" transformers.

For the transmission of power over long distances at voltages as high as 200,000 volts, transformers are used to increase to the transmission voltage the voltage generated by the electric generators. These transformers, which increase voltage, are known as "step-up" transformers.

In practice the arrangement represented in Fig. 6 would not be satisfactory, as there would be a large magnetic leakage. By magnetic leakage is meant that many of the lines of force created by the current flowing in the coil, P, radiate away from the iron core, in directions that prevent them from cutting the turns of the coil, S. The energy expended in forming these lines of force is therefore lost as far as use is concerned and the transformer would be of low efficiency as compared with transformers of modern design. To reduce to a minimum, this magnetic leakage, coils corresponding to the primary coil, P, and secondary coil, S, are carefully insulated and placed close together, in many cases being wound one upon the other, or subdivided and placed alternately side by side. By arranging the coils and the iron in this manner, practically all the flux (or lines of force) produced by the primary coil must pass through the secondary.

In the case of power transformers there are two general types of construction, namely, "core" type and "shell" type,

which reduce the magnetic leakage to a minimum. The names apply to the position of the iron with reference to the coils. When the coils are outside of the iron, the iron forms the core and the transformer has the core type construction. When the iron is on the outside of the coils the transformer has what is known as the shell type of construction, as the iron forms a kind of shell around the coils.

The electric transformer can be placed in almost any convenient place and, not having any moving parts to wear or get out of order, it requires an exceedingly small amount of attention. It does its work silently and efficiently.

Self-Induction.—It has been pointed out that when a current in one circuit is increasing or decreasing, there is an inductive effect upon any circuit in close proximity. This inductive effect is due to the change in the number of lines of force constituting the magnetic field, as it is called, which surrounds the circuit carrying the variable current. This varying magnetic field extends in all directions from the primary coil or circuit, and the secondary coil or circuit lies in the path of this magnetic field, so that the turns of wire are "cut" by the magnetic lines of force and voltage and current are produced.

It is obvious that the magnetic lines surrounding the primary circuit must "cut" across other parts of this circuit as they move inward or outward. There is, then, a current and voltage created inductively in the primary circuit itself. This "self-induction," as it is called, can be very great, as in the case of a coil of wire of a large number of turns, when the same lines of force "cut" the wire many times, the induction being cumulative.

The admission of current to the primary has the same effect as suddenly plunging the bar magnet into the coil; stopping the current will have the same effect as suddenly withdrawing the magnet. The current induced by plunging a magnet into a coil is one which tends to push the magnet out, while that induced by withdrawing the magnet is one which tends to draw it back. It therefore follows that the self-induced voltage, when current is started, tends to oppose this current, and prevent it from increasing as rapidly as it otherwise would; the voltage induced, on stopping the current, will tend to help the current to continue. The value of this self-induced

voltage may be considerable, since the rate of change from the maximum number of lines of force to the minimum is extremely rapid when the circuit is broken.

Nearly every one is familar with the "kick" from a coil when the circuit is opened. This "kick," which is due to the self-induced voltage, may be several times as great as the supply voltage, and in many cases, where equipment of considerable size is being handled, it is extremely dangerous to open circuits unless adequate electrical apparatus is available.

Capacity.—Whenever certain materials are rubbed by certain other materials static electricity is produced; in other words, the non-conductor becomes charged with electricity. This charge, however, resides only on the surfaces of the conducting bodies.

The density of the charge depends upon the number of units of electricity which have been imparted to the insulated body, and upon the area of the body. This charge has a certain "potential" or voltage in reference to other bodies. In order, therefore, to determine the capacity of any body, reference must be made to the voltage or potential which will be produced in that body by a given charge. A large quantity of electricity imparted to a conductor or body of small capacity will electrify it up to a very high potential, just as a large quantity of water poured into a vessel of small sectional area will raise the surface of the water to a comparatively high level in the vessel. Capacity is also comparable with the ability of a bottle to contain air. The addition of a given amount of air will raise the pressure, provided the temperature remains constant, and the amount of air required to produce a certain pressure in the bottle may be taken as the measure of the capacity of the bottle.

The capacity of a conductor is increased by bringing near it a stronger charge of the opposite polarity, and this principle is made use of in the construction of the condenser. A conductor that requires only one unit of electricity to raise its potential from zero to one, is said to possess unit capacity.

In the consideration of various circuits, capacity plays an important part. In the case of alternating currents it is often essential that additional capacity be connected or cut into the circuit, either to produce certain conditions or else to offset

certain other conditions. This results in the use of the so-called condenser which will be described later.

The effect of capacity is very noticeable in the case of high voltage transmission lines. The transmission line acts as a condenser, the air forming the outer coating and the wire itself the inner coating. When power is connected to the transmission line, electricity will flow into the wire until the capacity has been filled, although no electrical power is taken from the line meanwhile. This amount of power to supply the condenser effect may be momentarily, a large percentage of what later constitutes the power load. When the current is disconnected, this charge of current returns. The capacity effect is a very important factor in long-distance high-voltage work and must be seriously considered in the design of the transmission line.

The Condenser.—The manufactured condenser usually consists of a box made from insulating material, and inside of this box are placed a number of layers of tin-foil, separated from each other by insulating layers of paraffin paper or mica. All of the layers composing one set are connected to one terminal, and all of the other layers, to another terminal.

Condensers are used in a great many electrical circuits where special results are required. They serve as a momentary storage reservoir into which a sudden impulse or wave of current can go, and this excess of energy will be returned when the impulse has passed.

Their effect is analogous to that of a reservoir connected as a branch to a pipe line for carrying steam. When steam is first turned into the system the reservoir fills until it has the same pressure as the pipe line. If the line pressure drops suddenly for a moment the steam in the reservoir discharges into the system, and so maintains the supply. When the steam pressure returns, the reservoir fills and becomes ready to supply the excess steam.

From the foregoing, it is apparent that capacity tends to oppose and neutralize inductance. By proper proportioning of these quantities in any circuit, both can be counter-acted and neutralized.

Effects of Inductance and Capacity.—Inductance and capacity exercise a powerful influence upon an alternating cir-

cuit. The lines of force in the case of the alternating current are changing continually so that the inductance becomes an important factor. It is practically impossible to insert into an alternating circuit the right amount of capacity to completely neutralize the inductance or vice versa. However, when the inductance and capacity are approximately neutralized there is a condition set up which is analogous to a similar acoustic phenomenon and is spoken of as electrical resonance. Electrical transmission of energy is believed to take place by a series of waves, hence every circuit can have a natural period of vibration of its own as does a tuning fork. If voltage be applied to a circuit for an instant, a wave moves along it. An analogous phenomenon can be observed by striking a long wooden rod with a hammer. A vibration will travel along the rod. The period of vibration of the rod depends upon its elasticity and its density, and these qualities are analogous to the inductance and capacity of electrical circuits. If the period of vibration or resonance of the circuit is resonant to the applied voltage, then the waves of electrical energy will pass freely through the circuit.

CHAPTER V

THE GENERATION OF ELECTRIC CURRENT

The few preceding chapters have explained the meaning of several electrical terms. In this chapter the generation of electric current will be explained and reference will be made to many of the electrical terms previously discussed.

The electrical apparatus used for the production of electricity is known as a generator. The word "dynamo" is found in many articles and refers to the same apparatus, but in recent years this term has been very generally discontinued and the word "generator" has been substituted.

Faraday's Discovery—Fleming's Rule.—All generators are based upon the discovery made by Faraday in 1831, that electric currents are generated in conductors by moving them in a magnetic field. Faraday's principle may be summed up as follows: "When a conductor is moved in a magnetic field, so as to cut the lines of force, there is an electromotive force induced in the conductor, in a direction at right angles to the direction of the motion, and at right angles also to the direction of the lines of force."

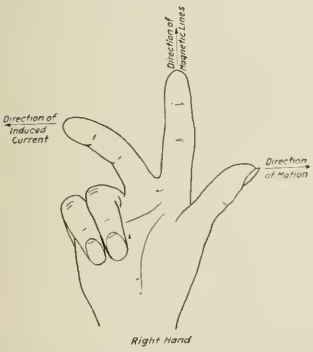

FIG. 7—Relation between Directions of Motion, Magnetism and Induced Current.

A useful rule for remembering this relation between motion, magnetism and induced current, is as follows: Hold the thumb, first and middle fingers of the right hand at right angles to each other, as illustrated in Fig. 7. If the thumb is pointing in the direction of the motion and the forefinger is pointing along the direction of the magnetic field (the lines of force are supposed to pass from the north pole to the south pole), then

the middle finger will point in the direction of the induced current. This rule is known as "Fleming's Rule." Another way of remembering the direction of the induced currents is to suppose a person swimming in a conductor and turning so as to look along the lines of magnetic force. If he and the conductor be moved towards his right hand he will be swimming with the induced current.

Magnetic Lines of Force.—It is a well-known principle that if a bar of iron has a number of turns of wire wound around it, and electric current is passed through these turns of wire, the iron bar becomes a magnet with lines of force radiating from the ends. The greater the number of turns of wire, or with a given number of turns, the larger the amount of current passed through the wire, the greater will be the strength of the magnet so formed, or, in other words, the larger will be the number of the lines of force. An induced electro-motive force or voltage is proportional to the number of the magnetic lines cut per second. In a generator, the magnetic lines radiate from the pole pieces around which are placed the field coils. The unit magnetic pole is one of such strength that when placed at a distance of one centimeter from a pole of equal strength, it repels that pole with a force of one dyne.

In order to get some idea of the magnetic lines of force, the whole of the space in the magnetic field should be conceived to be traversed by lines. These lines can be used to specify the direction of the magnetic field and also the magnitude. If the number of lines per square centimeter of cross-section of the field is imagined as equal to the number of dynes of force (on a unit pole), then there is brought to mind a sort of graphic representation of the strength of the magnetic field.

It has been stated that the voltage is proportional to the number of magnetic lines cut per second. Therefore, with a constant speed of rotation, the induced voltage will increase with the strength of the field, or, in other words, will increase with the number of lines of force radiating from the pole pieces. If the number of lines is kept constant, the voltage will increase with the increase in speed of rotation. In either case, the number of lines cut per second is increased.

Current Electricity.—In order to understand Faraday's principle, a clear conception of the generally accepted theory re-

garding the nature of a current of electricity should be had; no one knows what electricity is in itself, although some of the laws governing electrical phenomena are well known. One thing is certain, however, and that is, that the energy does not flow in the wire itself, but is transmitted adong the outside and around the wire. The presence of a magnetic field or magnetic lines of force surrounding a wire carrying electric current, is

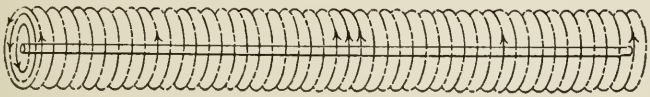

Fig. 8—A Magnetic Field Surrounds a Wire Carrying Electric Current.

also known. The wire is surrounded by a sort of magnetic whirl, as illustrated in Fig. 8. To set up this magnetic whirl requires an expenditure of energy and on breaking an electric circuit this surrounding energy returns or flows back into the circuit, tending to maintain the current and this causes the spark seen when the break occurs.

The Simple Generator.—In Fig. 9 is shown a simple generator, the armature of which is represented by only one coil of wire, but which serves as an illustration by which to explain the general principles relating to the transformation of mechanical energy into electrical energy. Consider the single rectangular loop of wire as rotating in a uniform magnetic field which exists between the poles of the large magnets, the direction of the lines of force, as stated previously, being from the north pole to the south pole. If the loop be placed at first in a vertical plane, the number of lines that pass through it will be a maximum, but as it is gradualy turned to the horizontal position, the number is less and less until the minimum or zero is reached. As the rotation continues, the lines begin to penetrate the loop from the opposite side, so that there occurs a reversal in the direction of the flow of current induced in the coil.. During one-half revolution, the induced currents will be in the direction from back to front in the part of the loop which is rising on the left and in the opposite direction, namely, from the front to the back, in that part which is descending on the right. If each end of the loop were separately

attached to metal collars on the shaft, and sliding contacts established between these rings and the ends of a circuit, an alternating current would be supplied to the circuit. All generator armatures are, in principle, similar to this simple one-coil armature. Although many turns of wire are added, each turn is affected by the magnetic field, according to the same laws that govern this single turn.

The Necessity for a Commutator.—There are two general classes of generators, direct-current generators and alternating-current generators. The reversal of current in a single rotating armature coil (Fig. 9) has been explained, and a similar reversal occurs in all armatures, whether of the direct

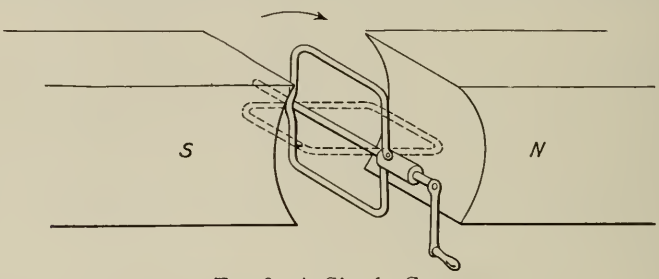

Fig. 9—A Simple Generator.

or alternating-current type. One might almost say that alternating-current is the normal type and direct-current a manufactured or derived type. In order to obtain direct current from any armature, it is necessary to make use of a commutator. This device usually consists of a series of copper bars, one for each coil. Sliding contact with these bars is made by means of brushes, which are set at such locations that the current from each coil is in one direction only. Each copper bar or commutator segment, as it is called, passes by the brush as a reversal of current takes place in the coil.

Again referring to the simple generator, Fig. 9, the value of the alternating current can be shown graphically as in Fig. 10. If a simple commutator was connected to this coil, then the reversed currents would be "rectified" and we would have a direct current, the value of which could be shown graphically as in Fig. 11. The current would be in one direction, but not continuous. A continuous value is approximated by using a large number of coils in the armature. For instance, if one

additional coil placed at right angles to the one illustrated, had been used in this simple dynamo, and connected to the commutator, a "rectified" current superimposed on the other current as shown by the dotted curves, Fig. 11, would have been obtained since this coil would be 90 degrees from the

Fig. 10—Graphical Representation of Alternating Current.

other coil. The current in the second coil would become zero in value when the maximum occurs in the first coil. It now may readily be seen that as more and more coils are added the

Fig. 11—Graphical Representation of Direct Current—Reverse Current Rectified.

variations become smaller and smaller until, with a large number of coils these variations are so slight that the current is practically continuous and of uniform value.

The Direct-Current Generator.—The direct-current generator produces in the circuit a practically constant and steady voltage. This voltage exists even when no demand is made on the generator, that is, when no electric current is flowing. The situation is analogous to that of a rotary pump, the function of which is to create a certain pressure, and the quantity of the liquid delivered depends on the friction or resistance of the pipe through which the liquid flows. If this pipe leading from the pump be entirely closed off, no liquid is carried away, but the rotation of the pump, nevertheless, maintains the pressure. The energy of the flow when the pipe is open is directly proportional to the product of the pressure given by the pump and the quantity of the liquid flowing.

A generator operating upon an open circuit has only to raise the electrical pressure or voltage between the brushes. No energy is expended in the circuit and the only energy required to keep up the rotation of the generator is that necessary to

overcome the frictional resistance of the machine itself, and to maintain the voltage. If electricity is demanded of the generator, say for the burning of lights or the operation of electric motors, the power delivered by the generator is directly proportional to the product of the current and the voltage. Therefore, the power required to drive the generator under these conditions is directly proportional to the output.

The Alternating-Current Generator.—The principles relating to direct-current generators apply in general to alternating-current generators. When in open-circuit operation a voltage between the brushes is generated, although this voltage is not constant as in the case of the direct-current generator, but varies from zero to a maximum and back again to zero, then to a negative maximum and back to zero. This series of current values complete what is known as a "cycle," and many of these cycles occur per second, according to the "frequency" of the generator. Upon connecting the generator to a circuit consisting of lights or of motors, a current will flow as in the case of the direct-current machine. Since the voltage is not constant, but varies, it would naturally be expected that the current would vary, and this is true, the variations being of the same number as the voltage variations, so that the voltage and current are usually considered as taking the form of waves.

Alternating current is generally employed for electric lighting and power when transmission over a long distance is necessary, as the principles governing its operation enable the cost of conductors to be reduced, since it is possible to use high voltages for transmission, and by means of transformers, reduce this high voltage to the suitable voltage for the load. The cross section of a wire necessary to transmit a given amount of electrical energy with a given percentage loss in volts, is inversely proportional to the square of the voltage used, that is, if the voltage is raised from 500 volts to 1,000 volts, the size of wire can be reduced to one-quarter the cross section and weight. The great advantage thus obtained by the use of high voltage can be realized either by a saving in the weight of wire or by sending the current over a greater distance with the same size of wire.

CHAPTER VI

THE ELECTRIC MOTOR

The electric motor operates in a reverse manner as compared with the electric generator; it receives electrical energy and changes it into mechanical form. The generator is based upon the discovery made by Faraday in 1831, that electric currents are generated in conductors by moving them in a magnetic field. The reverse condition would be to have a magnetic field and conductors through which an electric current is flow-

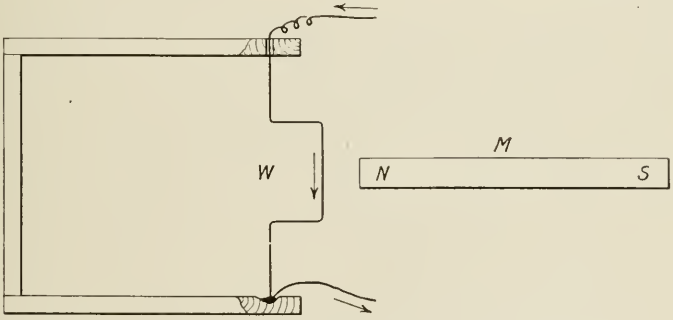

Fig. 12—A Simple Arrangement Illustrating the Principles of the Electric Motor.

ing, so that the conductors would have a tendency to move. This condition is exactly what occurs in the case of the electric motor.

Principle of the Electric Motor.—A simple but interesting experiment which illustrates the electric motor principle, is shown in Fig. 12. If an electric current is allowed to flow through the wire, W, from some source of power, say a battery, and this wire is suspended so that it can move, and the north pole of the magnet, M, is brought up close to it, then the

wire will tend to pass across the face of the magnet. If the other pole of the magnet is placed near the wire the movement will be in the opposite direction, or, if the same pole of the magnet is left in position, but the direction of the current in the wire is changed, then the wire will tend to move in the opposite direction. Changing either the direction of the current or the pole of the magnet produces a reversal in the direction of motion of the wire; if both the current and the pole are changed, however, the wire continues to move in the same direction.

The same condition will hold if the magnet is replaced by a soft iron or steel rod, on which are wound a number of turns of insulated wire carrying an electric current, as this rod will become a magnet, one end of which will be a north pole and the other, a south pole. The strength of the magnet and also of the force acting on the wire, W, are directly proportional to the number of turns of wire and the value of the current in the coils.

The direct-current motor of the present is based on the foregoing fundamental principle. The armature, composed of many wires or coils connected to the commutator, the purpose of which is to allow the electric current to pass from the source of power to the armature coils, is the same as the wire W; and the field, made up of several turns of wire mounted on iron or steel blocks symmetrically placed with relation to circumference of the armature, is practically the magnet M. Since the armature has many coils and the field is divided into four or more parts, there are, at any instant, many wires which are being attracted and many others repelled. The force of attraction or repulsion varies according to the distance from the field poles, and the torque or turning effort of the motor is constant. To obtain reverse rotation, the direction of the current must be changed in either the armature or field separately, but not in both, as the purpose is to change the relative polarity of the armature and the field.

The next factor to consider in order to appreciate the characteristics of the electric motor is the back, or counter, electromotive force.

Referring again to Fig. 12, if the source of power be dis-

connected from the wire, W, and this wire then is moved rapidly across in front of the magnet, or the rod on which are wound the turns of wire carrying current, there will be generated in this wire a voltage, which will vary in value, directly as the strength of the magnet and the speed at which the wire moves. If the ends of this wire are connected by some material which is a conductor of electricity, current will pass through the wire.

The principle described in the foregoing discussion affects a motor also. While the motor is running the armature coils are passing quickly by the field poles and a voltage or pressure in opposition to the voltage applied at the terminals of the motor is generated in the armature, and opposes the flow of electricity increasingly as the speed increases. This counter voltage which thus is generated in an electric motor is called the "back or counter-electromotive force"—commonly referred to as "e. m. f."

It is this counter-electromotive force (e.m.f.) that permits the resistances which are usually a part of a circuit, containing a motor, to be cut out as the motor gains speed. The only opposition to the current when a motor is standing still is provided by the combined armature and field resistance, which are comparatively small, and if full voltage was applied to the motor there would be such a rush of current that the motor would be destroyed. By inserting resistance, however, of such value that the current will not exceed a certain predetermined amount, the motor can be started slowly and the generation this counter e.m.f. begins at once. The resistance can be cut out step by step until no more is in circuit, at which time the speed is great enough to produce a counter e.m.f. of such value that the current passing through the motor does not exceed the safe amount. The motor will still continue to speed up, the current gradually decreasing and will reach a balanced speed when the difference between the impressed voltage and the counter e.m.f. generated, is a voltage sufficient to produce a current through the armature, such that the product of this current and the field gives the pull or turning power necessary to do the work required. It follows that if the field is strengthened the armature will not have to rotate

as rapidly in order to produce a given counter e.m.f., and vice versa. Increasing the field strength, therefore, results in slower speed, and likewise, when the strength of the field is decreased the speed of the armature, in turn, increases.

Types of Motors Used.—The types of motors used in railway service today are, the direct-current series motor, the alternating-current single-phase motor, the types of which can be further divided into the straight series type and the doubly-fed type; and the three-phase motor. With the exception of the three-phase, the above types have series motor speed characteristics, which, in general, are better suited for railway service than those of the three-phase constant speed. There are service conditions, however, such as those encountered on the Norfolk & Western, which are especially favorable to the use of the constant-speed motor.

The Series Motor.—The series type of motor receives its name from the method of connecting the armature and field, which are in series, i.e., the impressed current passes successively through the armature and field coils. In Fig. 13 are shown the diagramatic connections as arranged for a series motor.

For railroad work the series motor is generally used since in nearly every case its characteristics most nearly meet operat-

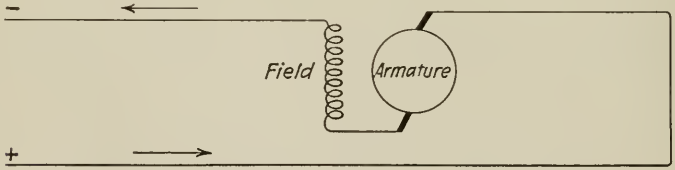

Fig. 13—Diagrammatic Connections of a Series Motor.

ing conditions. In the series motor the field strength varies automatically with the load; as the load increases, the field strength increases, and the result is an increase of torque with a decrease in speed. Within its capacity, therefore, this motor tends to adjust itself readily to the varying tractive effort required to accelerate a train and to propel it over the different curvatures and grades composing the railway right of way.

Additional facts concerning the direct-current motor are

given in the next chapter where a comparison is made with the alternating-current single-phase motor.

The Torque of a Series Motor.—The torque of a motor (derived from the Latin word *torquere,* to twist) is the pull which the armature of the motor exerts when current is passing through the windings. The torque of a motor differs from the thrust exerted by a steam cylinder, in that the value depends on the amount of the working medium rather than on the pressure. The amount of current passing through the windings of a motor determines the torque, while the pressure or voltage determines the speed of rotation. Although there is a certain relation between the current and the torque, there is no practical formula for calculating this torque, as other variables enter into the problem.

Electrical designers, knowing the number of turns of wire on a given armature, the number of turns of wire around the field poles, the air gap, and other factors in the design of the motor could calculate the torque, but for practical purposes the manufacturers furnish a set of curves, obtained by tests, and showing the relation between the current taken by the motor, the torque delivered, and the revolutions per minute (r.p.m.).

The torque is dependent upon two factors — the field strength and the ampere-turns in the armature. Each varies directly with the current so that in a motor whose field has not reached its saturation point—the point at which no more lines of force can penetrate—the torque is proportional to the square of the current. Railway motors frequently operate at the point of saturation, consequently the exact proportion does not hold.

The Speed of a Series Motor.—This motor's speed at a given voltage depends on the field strength and the number of armature conductors. The counter electromotive force generated in the motor must equal the voltage applied, minus the volts drop in the motor. The speed of the armature is thus fixed for any particular current, but is not directly proportional to the current. With an increase in current the drop in the motor increases, tending to reduce the speed; the increased current also increases the field strength and fewer revolutions

are required to generate the back electromotive force, so increased current results in decreased speed.

The Induction Motor.—As the induction motor is a constant-field machine, the torque is nearly directly proportional to the current. The speed cannot decrease with the load, so that large torque may exist at high speed resulting in a large horsepower output, requiring a large input of power. The three-phase induction motor used in railway work is discussed at length in Chapter VIII.

CHAPTER VII

THE ALTERNATING-CURRENT SINGLE-PHASE MOTOR

Alternating-current single-phase motors may be classified according to three types: the series commutator type, the doubly-fed type and the interpole type. The series commutator type is that used extensively on the N. Y., N. H. & H. R. R. electric locomotives, and operates on both alternating and direct current. The doubly-fed motor is that used on the P. R. R. multiple unit cars operated over the Paoli Electrification. The interpole type is a design of single-phase motor which also is now being introduced in railway service.

The Series Commutator Type.—In the preceding chapter it was pointed out that in the case of a simple motor (Fig. 12), if either the pole of the magnet or the direction of the current through the wire was changed, the direction of rotation of the wire would be reversed, but that if both were changed the rotation would be in the same direction. Because of this principle it is therefore necessary, in order to reverse the direction of rotation, to change either the leads to the armature or the leads to the fields. If the positive and negative leads at the terminals of the motor are changed, however, the direction of rotation will remain the same, as this changes the direction of the current in both the armature and the field coils.

Applying this reasoning to the case of a direct-current series motor, it is obvious that changing the connections at the terminals, say, by means of a switch, once a minute or oftener, would have no effect on the motor's direction. And if, instead of reversing the current by means of a switch, alternating current was connected to the motor, it would be logical to expect the motor to continue rotation in one direction, and operate satisfactorily, since with alternating current, which reverses in direction several times a second, the same condi-

tions would apply as when changing the connections at the direct-current terminals several times a second. While this theory is correct and the motor will rotate in the same direction, its operation would not be practical, since several conditions exist in the direct-current series motor when connected to an alternating-current circuit, which must be eliminated before the motor will work satisfactorily and be of commercial use.

In order to know what takes place it is necessary first to understand the winding of the armature of the direct-current motor and the connections to the commutator. In Fig. 14 is shown the development of the winding most generally used in

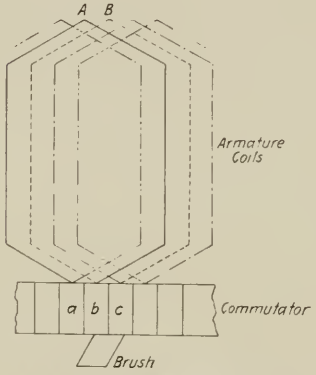

FIG. 14—Armature Winding Direct-Current Railway Motor.

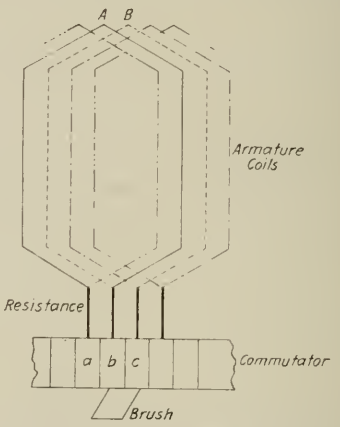

FIG. 15—Armature Winding Single-Phase Railway Motor.

railway work. From this sketch, it is seen that starting with one end of the coil, A, connected to the commutator bar, *a*, the other end of the coil connects to bar, *b*; the next coil, B, begins at bar, *b*, and ends at bar, *c*, and so on around the armature until the last coil ends at bar, *a*, and thus are all the coils connected together. It is also to be noted that the carbon brush is wider than any one of the commutator bars, so that the brush is in continuous contact with two at least, of the bars. In the position shown this brush is in contact with bars, *b* and *c*, and thus connects together the two ends of coil, B. As the armature rotates therefore, and as each commutator bar

passes under the brush, the ends of a coil are momentarily connected together by what is called a short circuit. As the brush is set exactly in the middle of the pole face, this short circuit exists when the coil is directly under the pole where it gets the maximum effect of the field.

Having explained the construction and connection of the coils of the armature, it remains to be seen what takes place electrically in this direct-current motor when connected to the alternating current. In order to appreciate fully the effect, those principles of induction which have been explained in connection with the theory of the transformer, should be recalled, as these same principles apply to the case of a direct-current series motor when connected to alternating-current circuits. There is the pole on which is wound the field coil and through which the alternating current is passing; there is also the armature coil directly in front of the pole which is closed by the carbon brush, as explained and illustrated in Fig. 14. There is, then, set up in this coil by induction, a local current which can reach a high value, and is entirely independent of the current taken from the supply circuit to do the work required of the motor. The resulting current can be of such a value that the motor would soon get very hot and be damaged, and, moreover, the commutation would be very bad, due to the heavy current at the brushes.

In addition, there is set up in the armature, a series of alternating fields. This condition, called the self-induction of the armature, is due to the alternating current from the power supply passing through the coils and must be eliminated before the motor can be operated successfully.

It is therefore necessary in order to have the direct current series motor run satisfactorily and be of commercial use with alternating current, to provide means for preventing or else reducing to a minimum, the two conditions just mentioned; namely, the local current in the short circuited coils, and the self-induction of the armature. To overcome the first condition, i.e., the large amount of current in the short circuited coil, there is placed in the same slot with each armature coil, and connected in circuit with the coil, a strip of German silver, which has a high resistance. The connections

are shown in Fig. 15. From this sketch it is seen that the coils are connected the same as in Fig. 14, the only difference being that two adjacent coils are not connected together at the commutator but to one end of a resistance, the other end of which is connected to the commutator bar. When the brush is in contact with bars, *b* and *c* as shown, coil B is short circuited and connected in series with it are two of the German silver resistance bars, so that the local current (due to the alternating field and the closed coil,) is limited to a minimum and safe value and good commutation can be obtained. The current from the supply circuit passes through the brush and also through only two resistances in addition to the armature coils in question, none of the other resistance bars being in circuit at a given time. When the armature is rotating, the brushes only short-circuit one coil momentarily, so that new resistances keep coming into the circuit and one set does not have the current passing through it continuously. The resistance, therefore, does not become overheated and does not interfere with the operation of the motor.

The second condition, namely, the self-induction of the armature, is taken care of by means of a winding placed in slots distributed around the inside of the motor frame, the arrangement being such that there is an alternating field opposite to that of the self-induction of the armature. The winding in these slots is called the auxiliary winding and is connected in series with the armature, thus the same current flows in each so that a field is produced which is not only opposite, but also equal to the self-induction. As a result of these features, this motor operates as satisfactorily as a direct current motor. Instead of being connected in series with the armature, the auxiliary winding sometimes is short-circuited on itself. The resultant effect is the same, as the current induced in the winding serves to offset the self-induction.

An example of three poles of the main field and a part of the auxiliary winding are shown in Fig. 16. The arrows indicate the direction of the current when the motor is operating on direct current and at a particular instant when using

alternating current. Upon entering the auxiliary winding, the current passes around the pole centres first, in a counter-clockwise direction and then in a clockwise direction. Instead of being bunched, the windings are spaced over considerable distance. The illustration shows only one main field coil together with a section of the auxiliary winding, but these windings continue around the frame of the motor.

The general appearance of the armature, frame, etc., is the same as that of a direct-current motor and the relations

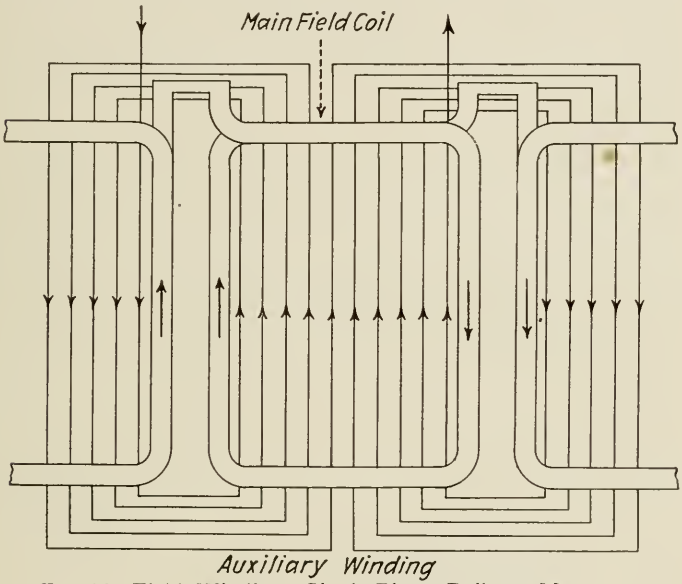

Fig. 16—Field Winding—Single-Phase Railway Motor.

of torque, speed, and current are in general identical with those of the direct-current series motor.

It has been shown what modifications are necessary in the direct-current series motor to obtain satisfactory operation on alternating current and it is interesting to know how successfully this modified motor operates when using direct current. The only changes were the inserting of resistance in the armature coils, and the placing of an auxiliary field winding connected in series with the armature. This resistance in the armature does not affect the operation of the motor

on direct current, and the auxiliary winding merely forms interpoles, except that the poles are distributed instead of having their coils located on iron pole pieces.

Interpoles.—Interpoles are used to increase the limit of operation of the motors over a wide range of current, voltage and speed. They are placed between the main field poles, and consist generally of small field poles, of which the windings are connected in series with the armature.

It has been only a few years since interpoles were first used, but now they are very common and are used extensively on motors for machine tools, elevators, presses, etc., and in other service where a wide range of speed may be required.

A motor can be built to suit almost any condition of service, but any great change from this makes what is called an unstable condition, and the motor will flash. In machine tool practice where many speeds covering a wide range are required for one machine, the interpole motor is essential for satisfactory operation. The interpole has also been embodied in the railway motor for street cars, multiple-unit trains, and electric locomotives.

Almost all of the difficulty and trouble, due to what are called surges, is avoided by the application of the interpole to the railway motor. A surge is a higher voltage than normal which travels momentarily and with decreasing power for some distance from the point where it is generated. It may be due to many causes, among the most common of which may be mentioned the sudden throwing-off of the power from the train, the "bucking-over" of a motor, and a flash from the conductor to ground. A surge is analogous to the pound in a water pipe which occurs when a valve is suddenly closed. This momentary rise in voltage, amounting perhaps to twice the conductor voltage, will be impressed on all the motors in the vicinity of the trouble, and will probably cause many motors to "buck-over." A motor having interpoles will last longer and will require less attention and repairs, than one which is not so equipped.

The Alternating-Current, Doubly-Fed Motor.—During the past few years the doubly-fed, single-phase motor has been

developed. In this motor the resistance leads in the armature are omitted and the armature and fields are not connected permanently in series. The motor starts as a repulsion motor with the armature short-circuited, and then operates as a doubly-fed series motor.

This motor has certain advantages over the straight single-phase motor. First, since the resistance leads are eliminated, the armature is simplified slightly; second, a higher alternating-current voltage can be used on the motor with a decrease in the current for the same motor capacity; third, the switching arrangement for the control of the motor is simplified and less expensive. A diagram of connections is shown in Fig. 17.

The motor has an auxiliary field winding, or cross-field winding as it is sometimes called, which is similar to that of the single-phase motor previously described, but is connected differently. The cross-field winding has twice as many effective turns as the armature, and the action of this winding

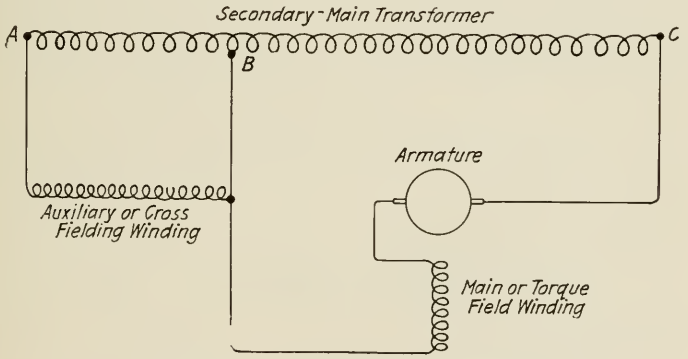

FIG. 17—Diagram of Connections for an Alternating-Current, Doubly-Fed Railway Motor.

and the armature winding is similar to that of a transformer. If the magnetizing current is neglected, then the total number of ampere turns in each winding must be equal and opposite. Consequently, the current in the auxiliary winding will be only one-half as large as that in the armature. Referring to Fig. 17, assume, for example, that the voltage across AC, the secondary of the main transformer, is 300

volts and due to certain load conditions, there are 1100 amperes flowing through the armature, The effective motor voltage depends on the position of the tap, B. If this tap, B, was connected at C, then the voltage across the auxiliary winding would be 300 volts and due to the transformer relation between this winding and the armature winding, the voltage induced in the armature and torque field winding would be 150 volts. Since the ampere-turns must be equal,

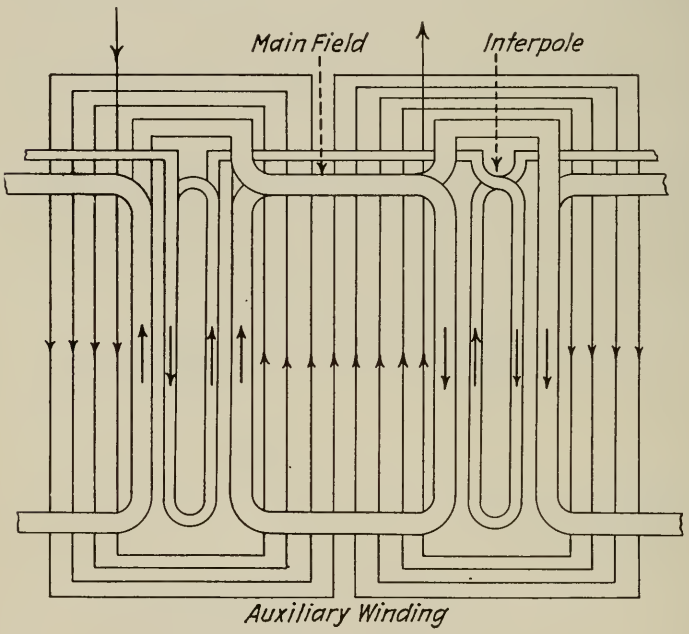

Fig. 18—Field Winding—Interpole, Single-Phase Railway Motor.

there will be flowing in the auxiliary winding 550 amperes in the opposite direction to the current in the torque field so that the tap, B, is only carrying 550 amperes. If tap, B, was connected at A, then 300 volts are connected across the armature and torque field and under the same load conditions of 1100 amperes flowing through the armature, there would be 550 amperes in the opposite direction as before, flowing through the auxiliary windings resulting in 550 amperes in

tap, B. Moving the lead, B, gradually from a point on the transformer winding near C towards A, the effective motor voltage can be changed from approximately 150 to approximately 300 volts. Here, then, is a means for controlling the speed of the motor by switching only one-half of the armature current.

The Alternating-Current, Interpole Motor.—During the past few years, progress has been made in the design of single-phase motors, the latest type of single-phase railway motors being known as the series-interpole type.

In this motor there are three fields: the main field, the auxiliary field, and the interpole field. The arrangement of windings around the frame is somewhat like that of the original single-phase motor illustrated in Fig. 16, except that the third or interpole field is located as shown in Fig. 18. The interpole fields are located between the main fields and are connected to give alternate positive and negative poles as in any motor.

This type of single-phase motor has an advantage over the doubly-fed motor, in that it has interpoles in addition to the distributed auxiliary winding. These interpoles accomplish

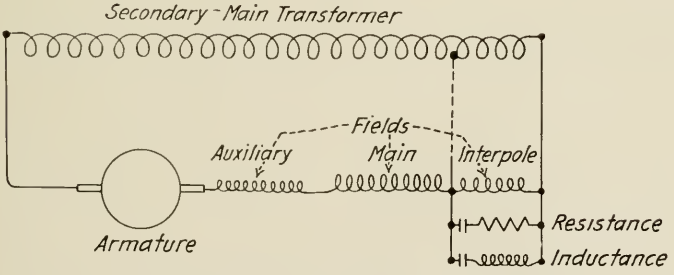

Fig. 19—Diagram of Connections for Single-Phase Interpole Railway Motor.

the same result as the interpoles in direct-current motors, i. e., an improvement in commutation which results in a reduction of weight for a given horsepower. At the same time, the interpoles applied to the alternating-current single-phase railway motor improve the power factor. Moreover, it is possible to vary the design of the interpoles over a wide range to accomplish or meet any particular operating con-

dition. It is possible with a fixed interpole coil to vary the strength and its effect on the motor operation by shunting the interpole coils with a resistance or an inductance. Due to this interpole flexibility, the motor lends itself to regeneration. These principles are illustrated by the simple diagram of connections shown in Fig. 19.

CHAPTER VIII

THE THREE-PHASE MOTOR

The three-phase induction motor is somewhat different from the other types. There are no electrical connections between the armature, or rotor as it is called, and the windings on the frame or "stator." The rotation is caused by induction and depends on Lenz's Law which in substance is as follows:—If a magnet or field is passed near a coil of wire there is induced in this coil a current which exerts a drag on the magnet or field tending to pull the same back. It is this induced current which causes the motor to operate, hence the name, induction motor.

Although the stator windings are evenly distributed around the frame, they are grouped electrically into a certain number of sets, according to the number of poles of the machine. The scheme of connections for the stator of a four-pole, three-phase induction motor is shown in Fig 20. Around the stator there are twelve groups—one group per pole for each phase—each consisting of six coils.

Unlike direct current, alternating current does not have a constant value, but changes. Starting at a value of zero it reaches a maximum, then decreases to zero again, and reverses to another maximum and back to zero, all of which takes place during a fraction of a second. This complete series of changes from zero back to zero is called a cycle, and a 25-cycle current is one in which there are 25 of these cycles per second. The action is similar to what takes place in the cylinders of a locomotive where the steam pushes the piston with varying force which is zero at points of reversal or ends of the strokes.

In a three-phase circuit the current is not a maximum in all three phases at one time, but at different times, and is similar

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to three cranks on an engine shaft 120 degrees apart, each connected to double-acting cylinders. Applying this fact regarding three-phase alternating current to Fig. 20, there are at a certain time, four-poles or fields, the centers of which are under the groups *a, a, a, a,* when the current in phase, A, is a maximum. This corresponds to one of the three cranks,

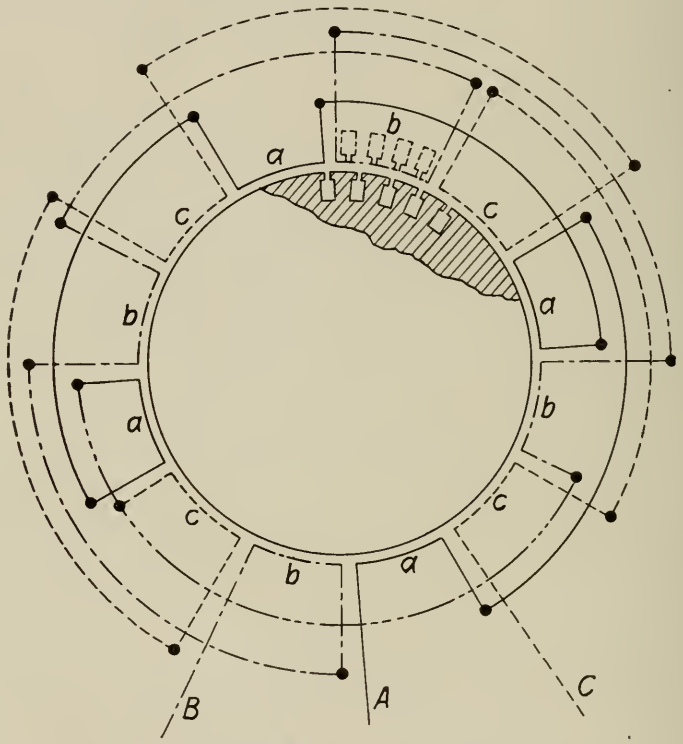


FIG. 20—Winding of Stator for Three-Phase Induction Motor.

exerting its maximum thrust. Due to the change of value of the current in the different phases in the next fraction of a second, the centers of the poles have moved under groups *b, b, b, b,* as the current in B phase increases and that in phase A diminishes, which corresponds to the No. 1 crank passing by the point of maximum thrust and No. 2 crank coming into the same position. The centers of the poles will next be at *c, c, c, c;* and due to the reversal will next be at *a, a, a, a,*

again, and will continue around the stator winding, keeping the same distances apart.

The speed at which this electrical rotation takes place in revolutions per minute depends on the number of poles of the motor, and on the number of cycles per second, or frequency, of the alternating current. The revolving field passing by the coils on the rotor, induces a current in them tending to stop this rotation of the field or poles. As the poles cannot stop, and the stator winding cannot move, the rotor is dragged along. When the motor is not doing any work, the speed of rotation of the rotor will be the same as the speed of the field or poles around the stator.

The formula for obtaining this speed is:

$$\text{rev. per min.} = \frac{2\ f\ 60}{p}$$

where f = frequency of the circuit (cycles per second,)
p = number of poles.

When load is put on the motor, the rotor does not maintain the speed at which the field rotates in the stator, which speed remains constant for constant frequency of the current, and this difference in the two speeds is called the "slip." The slip, starting torque, and current taken from the supply circuit, depend on the resistance of the rotor; the slip and the starting torque are directly proportional, while the current is inversely proportional within the limit of maximum torque obtainable from the motor.

The rotor of an induction motor can be designed with a very low resistance so that there is very little slip between no load and full load, and when designed in this manner the motor is called a constant-speed induction motor. This type is used where the power required is nearly constant, and where continuous service is necessary, such as for driving shafting, drills, blowers, compressors, circular saws, etc.

Resistances of various steps can be inserted in the rotor by connecting its windings to three small rings pressed on the motor shaft just inside the bearing, and providing brushes, which press on these rings so that the induced currents can be drawn off and passed through the desired resistances. Dif-

ferent speeds can be obtained by designing a resistance having different steps, as there will be a different speed of the motor corresponding to each resistance. Moreover, the stator winding can be so arranged that a fewer number of poles is obtained. For instance, with an 8-pole motor the windings can be grouped to form 4 poles and the speed will be twice that for 8 poles.

A small induction motor can be connected direct to the line without trouble, but when starting a large motor the method of inserting resistance in the rotor is used, as otherwise a great amount of current would be required. Motors having external resistance are used where frequent starts are made and where the power or speed required at the machine varies greatly. In railway service, a variable speed for starting is necessary, so that the resistance connected in the rotor circuit is cut out step by step as the speed increases until synchronous speed is reached. To give greater flexibility of operation, the control apparatus is arranged so that the number of poles of the stator can be changed.

CHAPTER IX

RAILWAY MOTOR CHARACTERISTIC CURVES —HOW TO READ THEM

As pointed out in the previous chapter, there is a relation between the torque delivered by the motor and the current used. The design of the motor determines what this relation is, and it can be calculated, knowing the number of turns in the field and armature, the amount of iron, air gap, etc. How-

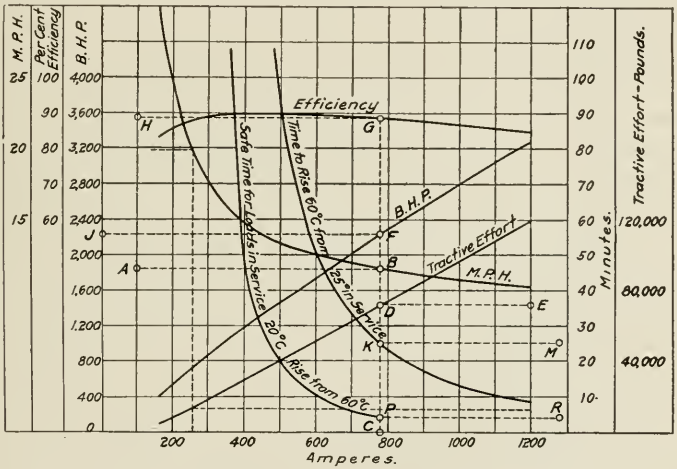


FIG. 21—Characteristic Curves of a Direct-Current Locomotive.

ever, in order to provide a ready means for one to calculate the tractive effort, or to determine the performance of an electric locomotive, a set of curves are drawn, known as the characteristic curves of the motor. These characteristic curves show the relation betwen the current, the torque, and the speed. By applying the gear ratio (if gears are used) and the wheel diameter, this data is then used in constructing a set of curves for the complete locomotive, the total torque of the motors being converted into tractive-effort at the wheels and the speed into miles per hour. A set of these character-

istic curves for a direct-current locomotive intended to operate on 2400 volts, is shown in Fig. 21.

Direct-Current Motor Curves.—It will be noted that all of the curves, namely: efficiency, miles per hour, brake horsepower, and tractive effort, are plotted as ordinates with the current as a base. This arrangement is especially convenient, since it provides a means by which the speed, tractive effort, etc., can be easily determined for any change of load.

How to Read the Curve.—To show how a set of curves is used it may be assumed that the locomotive under consideration (Fig. 21) is used for freight service, that it is equipped with four motors geared to 62-in. drivers and is hauling a load up a grade at the rate of 11.5 miles an hour.

We desire to know:

(a) How much current is taken from the line.
(b) Pounds tractive effort being exerted by locomotive.
(c) At what efficiency the locomotive is operating.
(d) What brake horsepower is being exerted.
(e) How long the locomotive could run under these conditions without more than 60 degrees C. rise when starting at an initial temperature of 25 degrees C.
(f) If the locomotive had already reached a constant temperature rise of 60 degrees C., how long could this work be handled before an additional rise of 20 degrees C. would be exceeded,

Referring now to the characteristic curves (Fig. 21), the information is obtained in the following manner:

(a) Starting at point, A, corresponding to 11½ miles an hour, follow the horizontal dotted line to the point where it cuts the speed—M.P.H—curve at point, B. From the point, B, which is the 11½-mile point on the speed curve, it is necessary to follow downward on the vertical dotted line to the ampere scale at point, C, which corresponds to 780 amperes, the current taken by the locomotive from the 2400-volt supply.

(b) The pounds-tractive effort corresponding to the current taken is found by projecting the point D—where the vertical line, BC, cuts the tractive-effort curve—horizontally to the point E, which corresponds to 72,000 lb. on the T. E. scale.

(c) The efficiency at this load is found extending the line BC until it intersects the efficiency curve at point G, then pro-

ceeding horizontally to the efficiency scale at point H, corresponding to an efficiency of 88.8 per cent.

(d) The brake horsepower is obtained by projecting horizontally the point F, where the vertical line BC, extended, crosses the B.H.P. curve, to the B.H.P. scale, at point J, corresponding to 2,240 horsepower.

(e) The time during which the motors will stand this load and not have their temperature rise exceed 60 degrees C., is obtained by projecting horizontally the point K, where the line BC intersects the temperature curve, to point M, which corresponds to 25 minutes on the time scale.

(f) The time during which this rate of working could be maintained and an additional rise of 20 degrees C. not be exceeded after the temperature of the motors had risen 60 degrees C., is determined by projecting point P—where BC crosses the 20-degree temperature curve—to the time scale at point R, which corresponds to 4 minutes.

As all of the curves are drawn with current as a base, a line drawn vertically from any value of current will cut all of the curves making up the set, which means—assuming the voltage as constant—that for a particular current, the characteristics of the locomotive are fixed and can only change with change in current. This also can be illustrated by an example.

It might be desired to know the tractive effort which the locomotive is capable of exerting when running at 20 miles an hour. Referring to Fig. 21, the point corresponding to 20 miles an hour on the M.P.H. scale, is projected over to the M.P.H. curve; the intersection corresponds to 255 amperes. This vertical line meets the tractive-effort curve at a point which, if projected to the right, corresponds to 14,000 lb.

As another example it may be assumed that the locomotive is handling a load requiring 40,000 lb. tractive-effort and the speed at which the train will operate is desired. First, the point corresponding to 40,000 lb. on the tractive-effort scale is found and projected over horizontally to the tractive-effort curve, then vertically to the M.P.H. curve, then to the M.P.H. scale, which shows that the speed will be 13½ miles an hour.

The Single-Phase Series Motor Curves.—While the characteristic curves of the single-phase, the doubly-fed, and the three-phase locomotives are different from those of the direct-

current locomotive, still they are all plotted in the same manner and the preceding descriptions of their interpretation apply to each. Often the characteristic curves are given for only one of the motors, of which there are several per locomotive. This practice is illustrated by Fig. 22, which shows the characteristic curves of a single-phase series motor. The

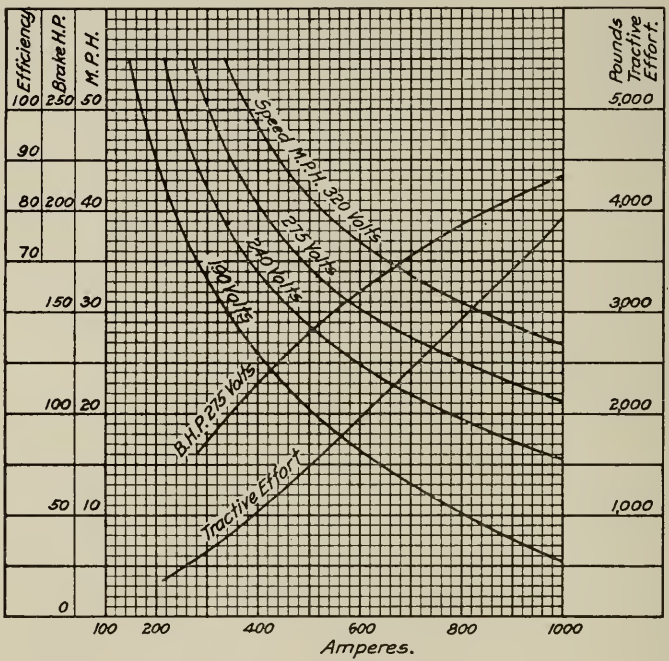


FIG. 22—Characteristic Curves of a Single-Phase Series Motor.

torque and r.p.m. curves of the motor have been converted into the tractive effort and speed corresponding to the gear reduction and wheel diameter of the locomotive. To obtain the performance of the complete locomotive it is only necessary to know the number of motors and multiply the current, tractive-effort, and brake horsepower by the number of motors. The M.P.H. curves will not change, as all the motors are geared alike.

It will be noted that speed curves are shown for several different voltages. Generally, if not always, with a single-phase locomotive it is possible to apply several different volt-

ages to the motors and variations in speed are obtained by the use of successive voltage taps. Since every tap is a running position, it is customary to show the speeds at the different voltages, so that the performance of the locomotive can be determined for any speed.

The Single-Phase Doubly-Fed Motor Curves.—The characteristic curves of the doubly-fed single-phase motor are shown

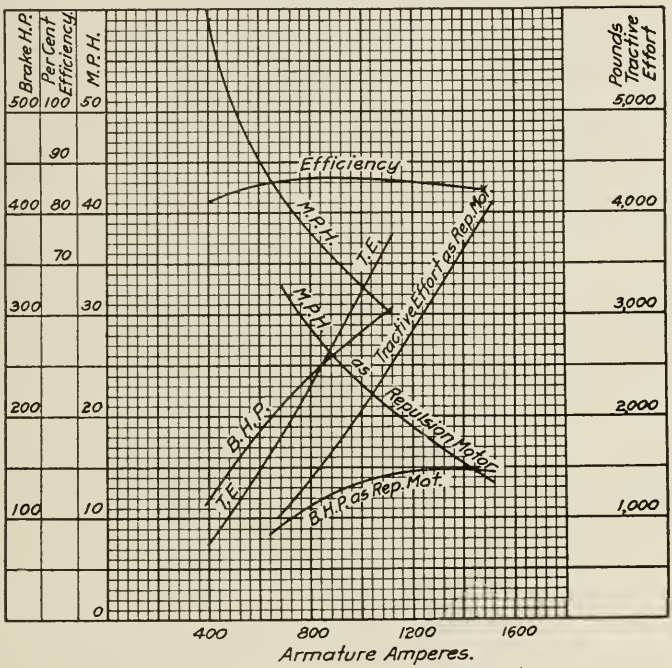


Fig. 23—Characteristic Curves of a Doubly-Fed Single-Phase Motor.

in Fig. 23. It should be noted that there are special tractive-effort and speed curves for the motor when operating as a repulsion motor, which is the arrangement when starting. It is necessary therefore first to use these curves and then to continue with the other—"doubly-fed"—set, after a certain speed has been reached.

The Three-Phase and Split-Phase Motor Curves.—The characteristic curves of a three-phase or split-phase locomotive are shown in Fig. 24. By the expression "split-phase" is meant equipment similar to that in use on the Norfolk & Western

Railroad. Current is taken from only one overhead wire and thus is single-phase current, but is changed to three-phase on the locomotive itself so that three-phase motors giving the constant speed characteristic, are used.

Two sets of curves are shown, as the motors are generally so designed that the number of poles can be changed, that is,

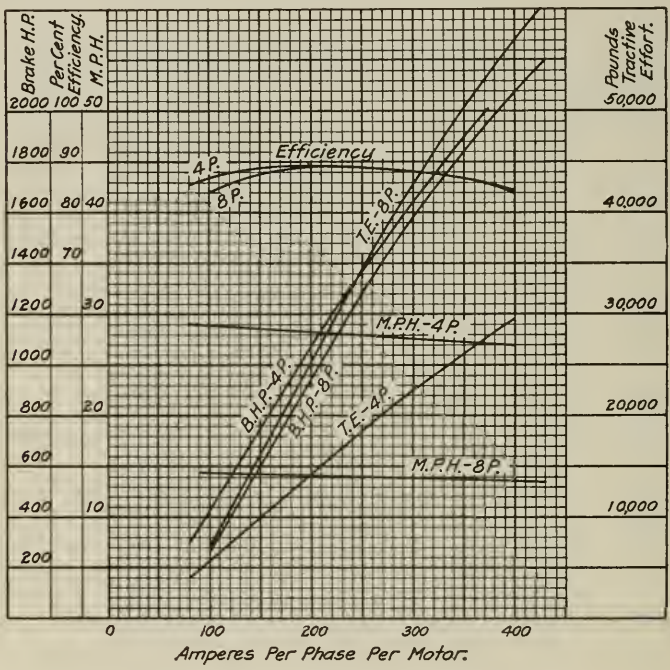


Fig. 24—Characteristic Curves of a Three-Phase or Split-Phase Locomotive.

the motors may be operated as 4-pole machines or as 8-pole machines. The rotation of the armature is twice as rapid, hence the speed of the locomotive is twice as great with the 4-pole combination as with the 8-pole combination. The locomotive in question has, therefore, two constant speeds: one, approximately 14 m.p.h., the other, approximately 28 m.p.h. The various curves bear the same relation, so that the problems set forth on the preceding pages can be applied to these curves also.

CHAPTER X

MOTOR COMBINATIONS FOR SPEED CONTROL

In the case of the characteristic curves of the direct-current locomotive, which were discussed in the previous chapter, only one speed curve is shown, the speed of the locomotive in the final running position when the maximum voltage is connected across the motors. This set of curves, however, must be supplemented by others showing the locomotive characteristics for the various motor combinations which are used in controlling the speed of the locomotive during acceleration. An electric locomotive could be driven by a single motor, but in actual practice a multiple number of motors are used. There may be any number, from two very large motors—as in the case of the Pennsylvania side-rod electric locomotives—up to 12 motors, as in the case of the latest types of the Chicago, Milwaukee & St. Paul locomotives.

Series-Parallel Connections.—With a number of motors available it is possible to arrange them according to different group combinations. They can be grouped in series so that the current which flows through the armature and field of the No. 1 motor also flows through the armature and field of the No. 2 motor, and so on to the No. 3 and to the No. 4 motor. When these motors are connected in parallel they are connected side by side, so to speak, and the current which flows through the No. 1 motor does not pass through the No. 2 motor, but each motor is so connected that it receives the full voltage of the line.

In the case of a four-motor direct-current locomotive, there is usually a combination midway between the series and the parallel. The four motors are arranged in two sets of two motors, each connected in parallel, and the two sets in series.

These combinations for a 600-volt locomotive are shown in Fig. 25. The upper group illustrates the series connections;

the middle group, the series-parallel; and the lowest group, the full parallel. These three combinations give three speeds, namely, one-quarter, one-half, and full speed.

In the series connection the voltage across each motor is only 150 volts, and as the number of revolutions a minute de-

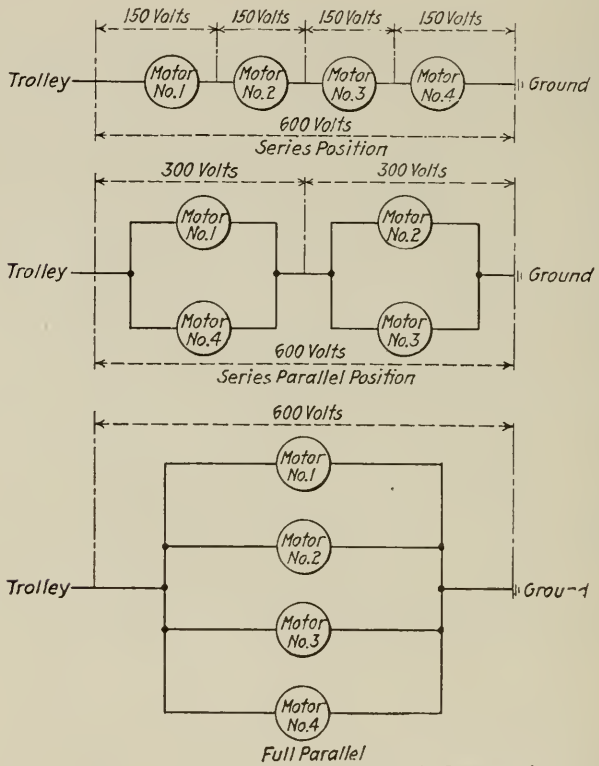


Fig. 25—Motor Connections for a 600-Volt Locomotive.

pends on the voltage, the speed will be only one-quarter what it is with 600 volts across each motor; in the series parallel connection the voltage across the motors is 300 volts, and hence one-half speed is obtained.

With the 12 motors previously mentioned as equipment for locomotives operating on 3000 volts, four speeds are obtained by changing the groupings of the motors. Owing to the

high voltage, each motor is not capable of operating with the full pressure across its terminals, so that for full-speed operation three motors are connected in series, with 1000 volts across each motor. Other combinations are made with twelve motors in series, six motors and four motors in series, to obtain one-quarter, one-half, three-quarters and full speed.

Field Control.—There is another method of securing additional speed control and more efficient operation with direct-current electric locomotives. This method is known as field control, and regulates the speed of the motor by varying the effective field turns.

The field control motor has two sets of field windings. In large motors these windings are separate, but in smaller motors there is usually only one set of field coils, each coil being provided with a tap, so that if connection is made to the proper tap lead only the desired number of field turns will be used. When starting the entire field winding is in circuit.

These motors will deliver the same tractive effort with less current than is required by the other types of railway motors described since the required field strength or ampere turns is obtained by using a comparatively large number of field turns instead of allowing for high amperage.

In the case of a series motor the field strength determines the speed so that with a full field, the speed will be lowest; cutting out part of the field turns weakens the field strength and the speed will be proportionately higher.

A great advantage of using field control is that many economical running speeds are available. To demonstrate this, the four-motor electric locomotive, with the arrangement of motors shown in Fig. 25, may be taken as an example. There are only three running speeds, as shown, but by making use of field control there would be six speeds, two in series, two in series-parallel and two in parallel, i.e., for each grouping there would be one speed with the motors running on full field and another with the motors running on short field.

The Pennsylvania electric locomotives are typical examples of what can be accomplished by field control. Switching from full field to short field is not accomplished in one step, but by three. At the first two steps resistances are placed in parallel with the field and thus weaken it by shunting some of

the current; the third step cuts out half of the field. From full field to short field, and while the locomotive is exerting approximately 20,000 lb. drawbar pull, the speed increases as much as 37 per cent.

The characteristic curves of the field-control motor used on the quill-drive high-speed passenger locomotives operating on the C., M. & St. P., are shown in Fig. 26. The voltage at the overhead wire is 3000 volts, so that with six motors in series the drop across each motor is 500 volts; with three in series, 1000 volts; and with two in series, 1500 volts. As shown by

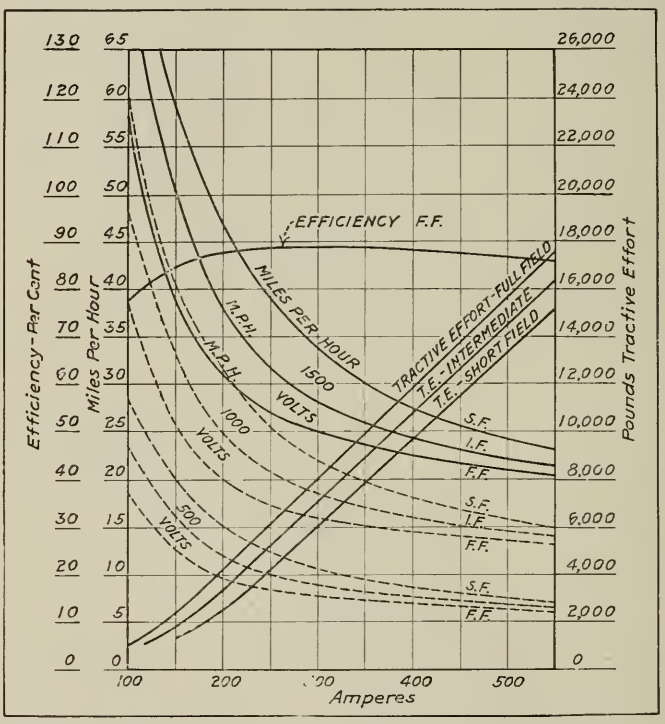


Fig. 26—Characteristic Curves of a Field Control Motor.

the curves there are for each voltage, three speeds corresponding to three different values of field strength.

Alternating-Current Motor Combinations.—Speed control in the case of the single-phase locomotive generally is not effected by different groupings of the motors, but by changing their voltage. The line voltage is "tapped" in such a

manner as to provide fractional voltages suitable for the various speeds; the motors remain connected in parallel.

Cascade Connections or Concatenation.—The motors of a three-phase alternating-current locomotive usually are operated in parallel. It is impossible to connect in series motors of this type as is done in the case of the direct-current motor, because the three-phase motor has no commutator and there is no connection between the field and the armature. Variations in speed are obtained by changing the number of poles or by what is known as the cascade connection.

Cascade control—sometimes called tandem control or concatenation, a word derived from the Latin and meaning "chained together"—requires the use of two motors at least

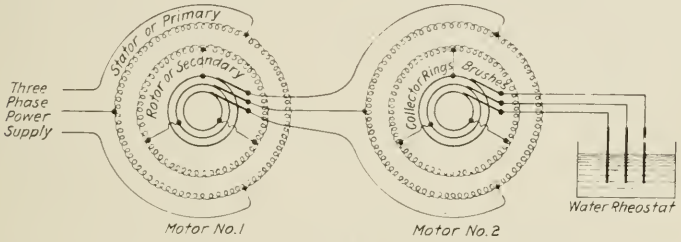


FIG. 27—The Cascade Method of Connecting Three-Phase Motors.

and these motors may have the same number of poles or a different number of poles and therefore a different number of speeds and different windings. The motors may be connected together mechanically, that is, on the same axle or on axles connected together by side rods; or they may be on different axles. The motors are said to be in direct concatenation when they tend to start in the same direction, and in differential concatenation when starting in opposite directions.

The electrical connections are substantially as shown in Fig. 27. The primary, or stator, of the first motor is connected to the power supply, and since there is no electrical connection to its rotor, the current is returned directly to the power house by way of the running rail. The secondary, or rotor, of this motor, is connected to the primary of the second motor through the collector rings. The circuit of the secondary of this second motor is closed through an adjustable resistance which may be a water rheostat. The induced

current from the rotor of the first machine passes through the stator of the second machine and by connecting wires returns to the first rotor. The induced current from No. 2 machine may be passed on to a No. 3 machine, and the same performance repeated.

The synchronous speed of an induction motor is expressed by the following formula:

$$\text{Revolutions per minute} = \frac{2\,f\,60}{p}$$

p = number of poles; f = frequency in cycles per sec.

With the cascade or concatenation arrangement, the secondary of the second motor when starting, is connected through the full resistance. As the locomotive speeds up, the resistance is gradually cut out until the secondary is finally short-circuited.

With two single-speed motors it is possible to get four speeds. The speed of two motors in direct concatenation equals $\frac{2\,f\,60}{p_1 + p_2}$, in which f is the frequency in cycles per second, p_1 is the number of poles in the No. 1 motor, and p_2 is the number of poles in the No. 2 motor. If the motors are connected in differential concatenation, the speed will be $\frac{2\,f\,60}{p_1 - p_2}$.

As an example, it may be assumed that the No. 1 motor has 12 poles, No. 2 motor has 4 poles, and the frequency of the supply is 25 cycles. The four possible speeds will then be:

(1) Motor No. 2 alone $\frac{25 \times 120}{4} = 750$ r.p.m.

(2) Motor 1 and 2 in differential $\frac{25 \times 120}{12 - 4} = 375$ r.p.m.

(3) Motor No. 1 alone $\frac{25 \times 120}{12} = 250$ r.p.m.

(4) Motor 1 and 2 direct $\frac{25 \times 120}{12 + 4} = 187.5$ r.p.m.

In the case of a locomotive, with two motors each having the same number of poles, the speed when the motors are connected in cascade, is just one-half of normal, as the denominator of the fractions would be twice that for single motor.

CHAPTER XI

GENERAL PRINCIPLES RELATING TO THE OPERATION OF TRAINS

In the design and operation of a system of electric traction for a steam railroad certain fundamental and definite problems are encountered by the railroad electrical engineer when making provision for handling the traffic of the road according to the existing time tables. Certain sizes and types of electric locomotives must be designed and built according to definite specifications. A careful study is made of the operating conditions; the grades, curves and speeds are considered; and, by calculations and graphic methods, it is possible accurately to specify the size of locomotives or cars required successfully to perform the service desired.

General Principles.—The capacity of the electrical equipment to perform a given service depends upon several factors, among which the most prominent are these: the profile of the line, including the grades and curves, the weights of trains to be operated, the number of stops and their location, and the schedule speed required.

It hardly requires mentioning that a line which has heavy grades, sharp curves, etc., will require electrical equipment of greater unit capacity than one having very few grades. It is also clear that the greater the train weight the greater the capacity required for the same speeds.

The number of stops and location of these stops also help to determine the capacity of the electrical equipment, since the larger the number of stops for the same schedule speed, the greater will be the capacity required. More time is consumed by the greater number of stops, and it is necessary to operate at higher speeds between the stops, hence requiring greater horsepower in order to maintain the same schedule.

The schedule speed is the distance in miles divided by the total time in hours. This must not be confused with the aver-

age running speed, which is the distance in miles divided by the actual running time and does not include the time taken by the stops.

Tractive Effort.—The power of a locomotive is applied at the rim of the driving wheels and the weight of the locomotive for a given pull must be such that friction sufficient to prevent slipping, will exist between the driving wheels and the rails. When this condition of stability exists, the power derived from the electric motors is transmitted through the mechanical connections to the rims of the driving wheels and the resulting pull is called tractive effort.

The amount of the tractive effort, which is usually expressed in pounds, has a definite relation to the torque of the motors, and is affected by the mechanical connections between the motors and the drivers. These connections may consist of gearing, or side rods, or a combination of both.

The torque of the motor is the pull at one foot radius so that the tractive effort (T.E.) can be easily determined from the following formula when the torque curve of the motor is available:

$$\text{T.E.} = \text{T} \times \frac{24}{\text{D}} \times \text{R} \times \text{E}$$

where T = torque in lb.
D = wheel diameter in inches
R = ratio of mechanical connection
E = efficiency of transmission

If gearing is used then the ratio of mechanical connections becomes the quotient obtained after dividing the number of teeth on the gear by the number of teeth on the pinion, and the efficiency is the gear efficiency. With side rods as used on the Pennsylvania electric locomotives, the ratio is unity, since the motors revolve at the same rate as the drivers.

The tractive effort of the locomotive is consumed in overcoming certain factors, namely, train resistance, grade resistance, and resistance due to curves. Train resistance is the force which must be overcome in order to maintain a constant speed on a straight and level track.

Grade resistance is equivalent to the tractive effort necessary to overcome the force of gravity as encountered when the car or locomotive is operating over a grade. The resistance

due to curves arises from the tendency for the locomotive to travel in a straight line. The centrifugal force which must be overcome in order to change the direction of motion, causes the wheel flanges to press against the outer rail and develop a frictional resistance which must be overcome by the expenditure of tractive effort. To accelerate a train requires the temporary expenditure of tractive effort in order to overcome the existing state of motion.

Train Resistance.—Train resistance depends on a great many variables which make it necessary to assume average conditions, and the effect which these assumptions have on the final results of calculations depends largely on operating conditions. In the case of rapid transit or local passenger service, the stops are often at such close intervals that the energy consumed during acceleration is a large percentage of the total consumption. Inaccuracies in train resistance, under these conditions, do not affect appreciably the results. However, in the case of long runs, where the train is accelerated infrequently, it is essential to use values for train resistance which are correct, as the energy required to overcome train resistance is then an important part of the total energy expended in propelling the train.

The train resistance is affected by the shape, weight and size of the car or locomotive and may be divided into three components, namely, wind resistance, rolling friction and journal friction. Wind resistance depends to a degree not yet determined, on the speed; the values of both rolling friction and journal friction are, for all practical purposes considered constant, although the energy consumed in overcoming them increases with the speed. At the instant of starting, the train resistance is comparatively high, depending on the design of the bearing, the wheel diameter, and the condition of the track. A value as high as 15 to 17 lb. per ton is probably reached, but drops rapidly to a much lower value at two to three miles per hour and then rises gradually as the speed increases. There are many empirical formulae for train resistance which agree closely with actual tests which have been made.

In working out the speed time curve, which will be explained later, a constant value of train resistance is assumed over the period of straight-line acceleration. Tests of train

resistance check fairly closely with the empirical formulae and in the working out of problems the curves which follow—Figs. 28, 29 and 30—will be found accurate and will give satisfactory results. These curves are conservative and do not give

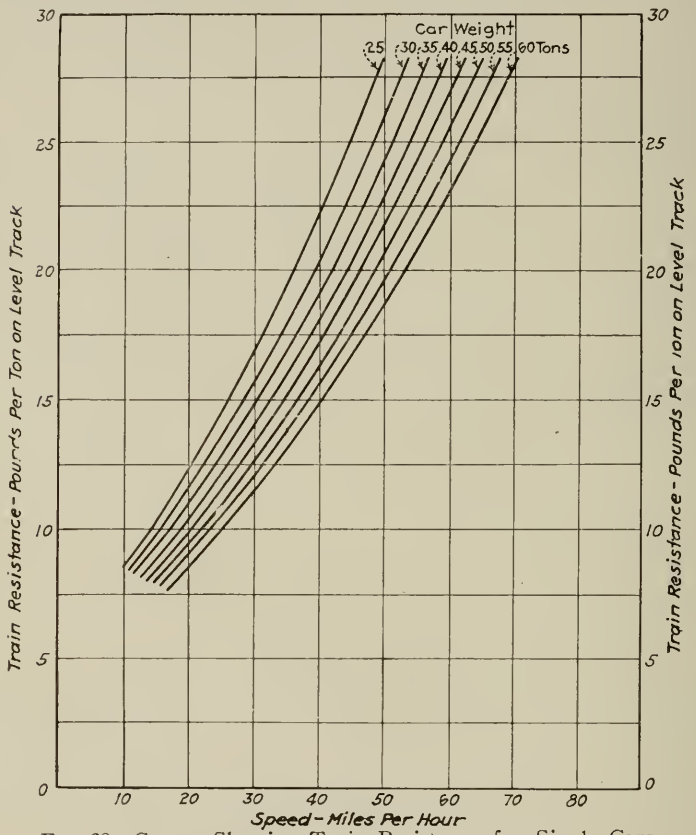


Fig. 28—Curves Showing Train Resistance for Single Cars Varying in Weight from 25 to 60 Tons.

as low train resistance values as some other curves based on formulae, or as low as the Berlin-Zossen tests made in 1903. These tests were made in Germany with a high-speed electric car of approximately 103 tons, operating over a specially prepared track suitable for very high speeds. Usually the problem is to determine motor capacity, so that these conservative values of train resistance are in the right direction.

Curves which are in practical use daily and which represent

average values for train resistance of single cars and of trains are shown in Figs. 28, 29 and 30.

For general use and quick calculations, the values which follow, can be used without referring to the train resistance

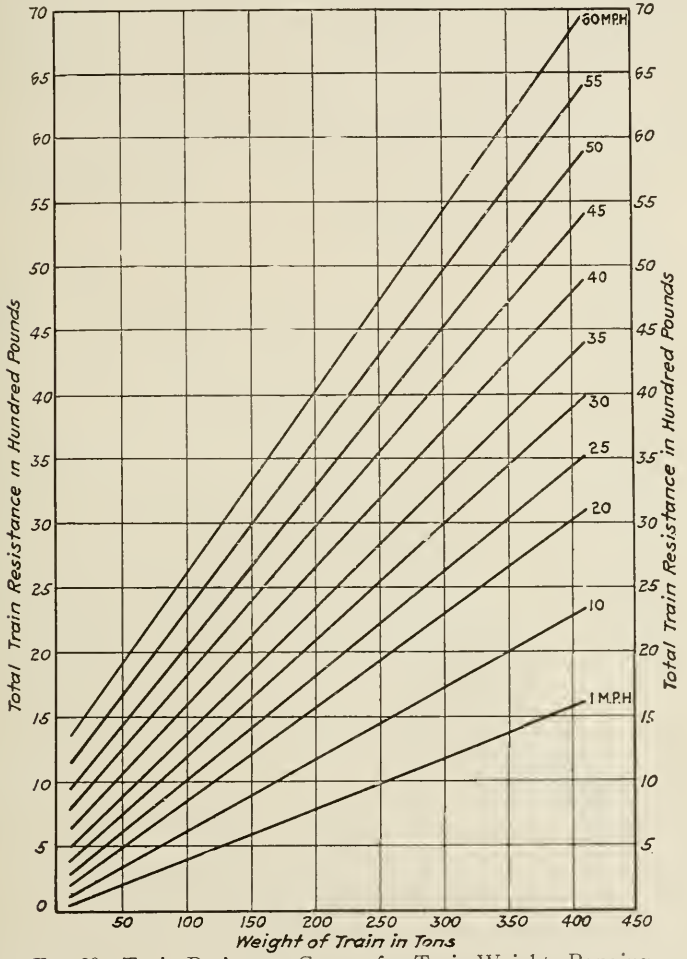


Fig. 29—Train Resistance Curves for Train Weights Ranging from 0 to 400 Tons and Speeds up to 60 m.p.h.

curves, although the curves should be used when any comparisons are to be made or speed-time curves constructed. Electric locomotive resistance is usually taken at 15 lb. per ton and the

trailing load for freight service at about 7 lb. per ton up to a speed of 30 miles per hour. With small light cars of approximately 30 tons weight a resistance of 20 lb. per ton up to 35 miles per hour can be used, but in the case of heavier cars—50 to 60 tons—15 lb. is suitable up to a speed of 35 to 40 miles per

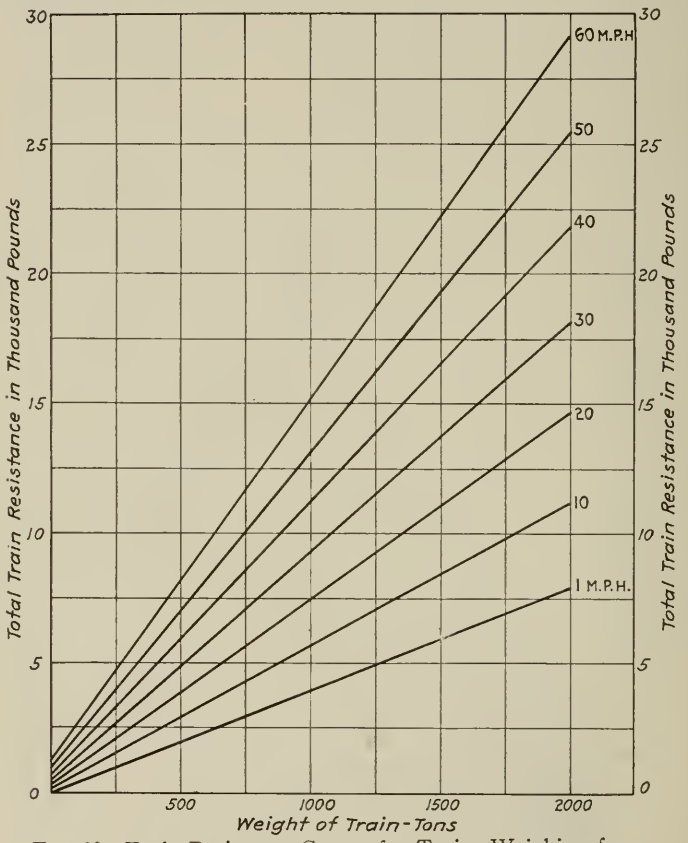


Fig. 30—Train Resistance Curves for Trains Weighing from O to 2000 Tons and Speeds up to 60 m.p.h.

hour, and 22 lb. at speeds above 40 and up to 60 miles per hour. When trailer cars are used in multiple-unit trains then the additional resistance allowance for these trailer cars can be taken at 12 lb. per ton for speeds up to 50 miles per hour and 13 lb. per ton from 50 to 60 miles per hour.

Acceleration.—The rate at which trains are accelerated varies greatly. In rapid transit service, usually handled by

multiple-unit operation, values from 1.5 to 2 miles per hour per second are used. For electric locomotives in freight service, the acceleration rate is much lower and values of 0.1 to 0.2 miles per hour per second are used, while in passenger service, electric locomotives accelerate at a rate of about one mile per hour per second.

The force necessary to produce this acceleration is proportional to the product of the mass—weight divided by 32.2—and the rate of the acceleration, and may be expressed in the following formula:

$$F = \frac{W \times A}{32.2}$$

where W = weight of body in lb.

A = rate of acceleration in feet per hour per second. (The value, A, is 1.47 for 1 mile per hour per second acceleration.)

Using one ton or 2,000 lb. in the above formula and a rate of acceleration of one mile per hour per second (m.p.h.p.s.) a value of 91.1 lb. per ton is obtained. This is the tractive effort per ton required to obtain rectilinear acceleration only and does not take into consideration the additional force necessary to overcome the inertia of the wheels, armatures of motors, etc. A figure of 100 lb. is used, therefore, as the total tractive effort per ton to produce a rate of acceleration of one mile per hour per second.

For any other rate of acceleration the value to be used is proportional; for instance, with a rate of acceleration of ½ m.p.h.p.s., 50 lb. per ton would be required, or if 1¼ m.p.h.p.s., 125 lb. per ton. When starting a train, the acceleration is usually rapid, and it is at this time that the greatest amount of tractive effort is exerted, but this acceleration gradually decreases until uniform speed is reached when the only tractive effort required is that necessary to overcome train resistance.

Grade Resistance.—The grade resistance is the tractive effort expended in lifting the car through the vertical distance ascended by the grade. For a 1 per cent grade the force required is 1/100 of the car or train weight; in terms of tons, it is 20 lb. per ton, and for any other grade, the resistance is

directly proportional. If, for instance, the train is operating on a 2 per cent grade, 40 lb. per ton would be used, or if operating on a 0.75 per cent grade, 15 lb. per ton would be used.

Curve Resistance.—The value of curve resistance in terms of degree of curvature is at its best only approximate, as there are many factors such as track, road-bed, and speed of train which enter into and affect all calculations. A value of

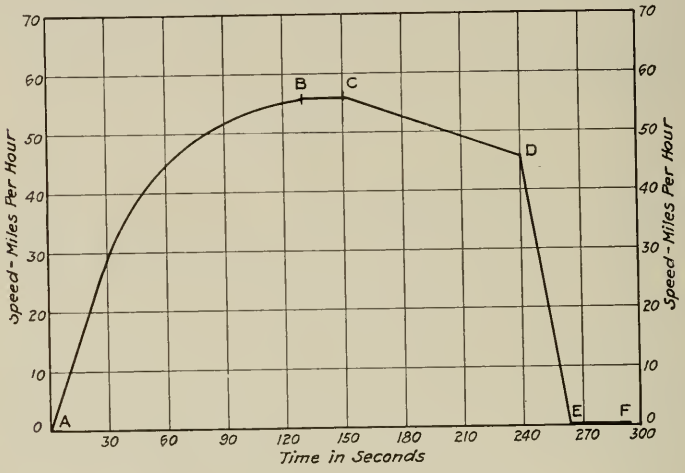


Fig. 31—A Typical Speed-Time Curve.

0.8 lb. per ton per degree of curvature is generally used, although a figure as low as 0.4 lb. may be taken when the construction of the road-bed is of a high order.

Speed-Time Curve.—The movement of a train can be represented graphically by what is known as a speed-time curve. The usual train movement consists of a series of runs, the number depending on the number of stops which the train makes between two terminals of the road. After each stop, the train must accelerate, at first rapidly and then more slowly, until a balanced speed is reached and this speed is maintained until a point is reached when the power is cut off and the train coasts until the brakes are applied to bring the train to a standstill at the next stop. Each of these cycles of operation can be shown graphically by plotting speed against time, as shown in Fig. 31. Acceleration is shown by

the line AB; the constant speed, by BC; coasting, by CD; braking, by DE; and the stop, by EF.

Often it is possible and convenient, where there are a large number of stops to choose a typical run, which will represent an average of the runs between each of the stops and therefore will represent the conditions to be met by the electrical equipment, and the curve in Fig. 31 could be taken as typical for a particular service where the average length of run, including stop, is 294 seconds. When using this typical example, some grade must be assumed which will represent the average of all the grades. Even if the ends of the line are at the same elevation, energy is expended by the train while running over a rolling country, since all of the power stored by lifting the cars and locomotive is not available for coasting on the down-grades. The equivalent grade represents the average grade and is obtained as follows:

$$\text{Equivalent Grade (in per cent)} = \frac{100 \times S}{2 \times L}$$

where S = sum of rises (in feet) in both directions
L = length round trip (in feet)

Examples.—The following examples have been assumed to show how the various values of train resistance, grade resistance, etc., are used and applied:

1. It is desired to know the tractive effort required to propel a 55-ton car up a 1.23 per cent. grade at 35 miles per hour.

To overcome train resistance and propel a 55-ton car at 35 miles per hour will require 13.75 lb. per ton (value obtained by referring to resistance curves, Fig. 28).

$$55 \times 13.75 = 756 \text{ lb.}$$

To lift the car up the grade will require

$$55 \times (20 \times 1.23) = 1{,}353 \text{ lb.}$$ (see Grade Resistance.)

The total tractive effort will then be

$$756 \text{ lb.} + 1{,}353 \text{ lb.} = 2{,}109 \text{ lb.}$$

2. The required tractive effort if there was a 6 degree curve on this grade is found in the following way:

Assuming 0.8 lb. per ton as curve resistance per degree of

curvature, the tractive effort on account of the curve would be:

$$55 \times 0.8 \times 6 = 264 \text{ lb.}$$

The total tractive effort to overcome train, grade, and curve resistance will be:

$$2{,}109 \text{ lb.} + 264 \text{ lb.} = 2{,}373 \text{ lb.}$$

3. The effect of acceleration is illustrated by assuming that it is required to accelerate at the rate of 0.6 m.p.h.p.s. against this grade and curve.

The tractive effort to accelerate at the rate of 0.6 m.p.h.p.s. is:

$$55 \times 60 = 3{,}300 \text{ lb.}$$ (See subject, Acceleration.)

There will still be required the same tractive effort for the grade, curve, and train resistance so that the total tractive effort is:

$$2{,}373 + 3{,}300 = 5{,}673 \text{ lb.}$$

Horse-Power.—Sometimes it is interesting to know what horsepower is being developed by a locomotive. This may be easily determined when the tractive effort and speed are known. The formula is:

$$\text{H.P.} = \frac{\text{Pounds tractive effort} \times \text{miles per hour.}}{375}$$

CHAPTER XII

COMPARISON OF THE OPERATING CHARACTERISTICS OF STEAM AND ELECTRIC LOCOMOTIVES

Some of the advantages of electric operation as compared with steam operation of railways have been touched upon in Chapter I. Electrical engineers have been required to analyze service conditions very thoroughly, and in the comparisons made, the general characteristics and limitations of the steam locomotive as viewed from the standpoint of the electrical engineer have been considered. When the characteristics of the two types of machines, namely, the electric and the steam locomotive, are compared, the electric locomotive is found to possess features which make it superior for certain phases of railway operation and the benefits apply not only to passenger trains, but also to the heaviest freight trains.

Equated Tonnage Rating.—Loads assigned to a locomotive must be of such a maximum value that a certain percentage of tractive effort will be available for possible starting under maximum grade and load conditions. The locomotive must be rated in terms of its maximum load in tons for the division or divisions over which it operates, and during the winter months this maximum tonnage must be corrected for temperature. This rating is called the "equated" tonnage rating, and is mentioned because it corresponds somewhat to the continuous rating of the electric locomotive, which will be discussed later in this chapter. In case a load requiring greater tractive effort should be imposed it would not be possible for the steam locomotive to start this load, even if the coefficient of friction was raised by means of sand blown under the drivers.

As the speed of a steam locomotive increases, the available tractive effort decreases slowly, until a point is reached at which the boiler can no longer supply the steam required by the cylinders at full stroke. To attain higher speeds the cut-off must be shortened, and this results in reducing still further

tractive effort. It is evident, then, that the dimensions of the cylinders and driving wheels do not alone determine the available tractive effort, but that the steaming capacity of the boiler also enters, and a definite relation exists between the rated tractive effort and heating surface and grate area.

Tractive Effort Formula—Steam Locomotive.—The steam locomotive consists of two distinct units, the boiler and the engine, each of which is designed for the service in which the locomotive is to be used. The boiler is limited in size, owing to the space available, and often must be worked to its limit in order that the required amount of steam shall be generated. The pressure which the boiler is able to sustain, and the mechanical dimensions of the engine determine the tractive effort available at the drivers. The tractive effort of a simple locomotive can be easily calculated from the following formula:

$$TE = \frac{0.85\,P \times C^2 \times S}{D}$$

where TE = rated tractive effort in pounds at the rim of the driving wheels.

P = boiler pressure in pounds per square inch.

C = diameter of cylinder in inches.

S = piston stroke in inches.

D = driving wheel diameter in inches.

It will be noted that the only variable in this formula is the boiler pressure, so that with full boiler pressure in the cylinders, the maximum tractive effort is obtained. A steam locomotive, however, cannot work steam for the full length of the stroke, so that the rated tractive effort as obtained from the preceding formula will be delivered at starting only. This maximum tractive effort corresponds in general to about 22 per cent, as the coefficient of friction between the drivers and the rails, that is, with this coefficient, which represents good rail conditions, a locomotive as generally designed has just enough power to slip the wheels.

Tractive Effort Formula—Electric Locomotive.—The electric locomotive consists of a single unit. The electric power required for its operation is transmitted—often for several miles—over wires or some other form of conductor, and by

means of control apparatus, is delivered to the motors. The motors are mechanically connected to the drivers, and are directly responsible for the power which the electric locomotive delivers in the form of tractive effort.

The tractive effort of the electric locomotive depends on the motors and the manner in which they are connected to the drivers. As these motors are usually all of the same size and design, the total power of the locomotive is a multiple of the power which one motor can exert. Knowing the electrical characteristics of each motor, it is possible to determine the total power of the locomotive.

The only fixed factor which enters into the calculation of the tractive effort is the wheel diameter. The force from the motors, i.e., the turning moment or torque, is dependent upon the electrical characteristics which vary with the amount of current taken by the motor.

The torque of the motor is the pull which it can exert at one foot radius from the center of the armature shaft, i.e., at any point in a circumference of a circle 24 in. in diameter, from which it follows that the formula for the tractive effort of an electric locomotive is:

$$TE = \frac{T \times 24 \times G \times \text{gear efficiency} \times N}{D \times g}$$

Where TE = tractive effort in pounds.
T = torque of motor in pounds.
G = number of teeth in the gear.
g = number of teeth in the pinion.
D = diameter of the drivers in inches.
N = number of motors.

This formula is a general one and considers gearing as the mechanical connection between the motors and the drivers. When gearing is used, the speed of the driving axle is changed from that of the motor shaft according to the ratio, $\frac{g}{G}$. As the power is the same at the motor shaft and at the driving axle, except for the gear loss—expressed in the formula as

gear efficiency—the torque at the axle must increase according to the ratio, $\frac{G}{g}$. Since the torque is measured at one-foot radius, and the tractive effort at the wheel treads, the tractive effort will be to the torque as $\frac{24}{D}$. When side rods and no intermediate gearing are used, g and G are eliminated, as is also the gear efficiency.

The Torque.—The torque of the motors of an electric locomotive cannot be compared strictly with the action of steam in the cylinders of a steam locomotive. In the former case, the value of the torque, and hence the tractive effort, depends on the amount of current passing through the motors, while the resulting tractive effort due to steam depends on the pressure. The amount of current to the motors is so controlled that, within limits, as large a torque as desired can be obtained. The maximum tractive effort, therefore, is not fixed, and is not dependent on a maximum constant pressure, as is the case with the steam locomotive. There is, however, a relation between the torque delivered by the motor and the current used. The design of the motor determines what this relation is, and it can be calculated from the number of turns in the field, armature, etc., but there is no practical formula.

In order to provide a ready means for calculating tractive effort and the performance of an electric locomotive under consideration, a set of curves are drawn, known as the characteristic curves. These characteristic curves show the relation between the current taken by the motor, the torque developed, and the speed. This data is then used to construct another set of curves for the complete locomotive, so that it is possible to read directly the total current taken by the locomotive, tractive effort in pounds, and the corresponding speed in miles per hour. The tractive effort is obtained by the formula given, and the miles per hour, from the formula:

$$\text{M.P.H.} = \frac{\text{r.p.m.} \times D \times g}{G \times 336}$$

It has been previously explained that the tractive effort depends on the amount of current which passes through the motors, this current value being subject to control. In addi-

tion, the large supply of power at the power house is available for developing the maximum power of the electric locomotive, which, therefore, is not held to a fixed condition, as is the steam locomotive by the size of its boiler. Instead, it is possible to take advantage of extra adhesion which may be natural or caused by the application of sand, a value as high as 35 per cent having been obtained. It is, then, a question of placing sufficient load on the drivers to obtain the maximum drawbar-pull required.

It is not possible to maintain this high maximum tractive effort continuously on account of resultant damage to the motors, but there is a tractive effort which can be developed continuously without injury to the locomotive. This leads up to what is known as the continuous and hourly ratings of an electric locomotive.

Continuous and Hourly Rating.—The equated tonnage rating of the steam locomotive, which is the tonnage the locomotive can normally handle has been explained as being determined by the load handled, the profile of the road, and the temperature of the atmosphere, low temperatures strongly affecting the rating. This rating corresponds, as nearly as the two entirely different machines can be compared, to the continuous rating of the electric locomotive. The continuous rating is fixed, but is determined in a different way than the equated tonnage rating, which signifies the maximum load that it is safe to haul if the train is to be gotten over the road, allowance being made for a reduction in tractive effort due to poor coal and other factors.

The continuous rating of the electric locomotive, however, does not mean the maximum load which the locomotive will be able to take over the road; it will pull a heavier train and do it on schedule, but this may be accomplished at the expense of overheating the motors, and the question of whether damage will result, depends on the time the overload is maintained. This feature of electric locomotive operation makes necessary the use of what is known as the hourly rating which is in addition to, and higher than the continuous rating. The hourly rating represents the tractive effort which could be exerted for one hour without overheating the motors, provided that the locomotive is cool when the extra load is ap-

plied. This rating does not exist in steam locomotive practice.

When working at the high rating it is obvious that the current drawn by the motors is of comparatively high value and it is this current's heating effects that limit the time during which the overload can be endured. The current, in passing through the motors, causes the fields and armatures to heat, because of the resistance of the conductors. This heat is conducted away by radiation through the windings and the iron, and thus the entire motor becomes heated. A certain constant current through the motor continuously, will result in a certain temperature rise above the surrounding air, and the extent of this temperature rise will depend on the value of the current. While the electrical insulation used in the motor will not be injured if occasionally a temperature of 100 degrees C. is reached in service, the ratings of the motors are for a much lower temperature rise, namely, from 60 to 70 degrees C.

A continuous current which will give a temperature rise of 60 degrees C. is the continuous current rating and the tractive effort corresponding to this continuous current rating is the continuous tractive-effort rating of the locomotive. The hourly rating is that higher current—and the tractive-effort is correspondingly higher—which, in one hour, causes the rise of 60 degrees C.

Likewise, there can be an indefinite number of ratings for for as many intervals of time up to the continuous time. It is the practice, however, to give only the continuous and hourly ratings, although very much larger current can be taken for a shorter time without exceeding the allowable temperature rise, and so it is possible to rate the locomotive at a much higher tractive-effort for a short-time performance.

It is now clear why it is possible with an electric locomotive to get a large tractive effort for starting or for emergency conditions, and why this same tractive effort cannot be used continuously. The loads must be adjusted and regulated; if the locomotive is worked above its continuous rating for short periods it is necessary to have coasts, stops, layovers, or sections where the current requirement is below the continuous rating, so that the average heating effect will not exceed the safe temperature rise. This is of vital importance in the

operation of the electric locomotive, but does not apply to that of the steam locomotive, for as long as the boiler of the latter has plenty of water, no harm can be done by operating continuously at very high percentages of the maximum drawbar-pull.

It was mentioned that the equated tonnage rating of the steam locomotive could be likened to the continuous rating of the electric locomotive. There is, however, one important point which makes the two comparisons unrelated. The equated tonnage rating of the steam locomotive, being the rating for a particular division, varies with different service conditions and, is governed by the maximum grade, or by the pull which is required of the locomotive, so that the load is governed by this maximum condition. In the case of the electric locomotive, high tractive efforts can be exerted for short periods of time so that the loading does not necessarily depend upon the maximum grade encountered, but upon the profile as a whole. The load will be governed by the average temperature of the motors, not by what the maximum pull may be for 5 or 10 minutes. This factor makes it possible to give an electric locomotive a tonnage rating which is higher in proportion to the weight on the drivers than would be possible for a steam locomotive operating over the same profile.

There is one more very important point which should be thoroughly understood and appreciated, when considering the electric locomotive, and that is the horsepower rating. Horsepower is the product of the tractive effort and the speed; it is a direct measure of the locomotive's capacity to do work. Tractive effort determines the trailing load which can be handled, but it is the horsepower that is a measure of the hourly ton miles. A railroad often is not so much concerned in the maximum tractive effort or drawbar-pull which a locomotive can exert, as it is in the speed at which a certain drawbar-pull can be developed. In respect to their ability as regards the latter, electric locomotives excel steam locomotives and this has been one of the important reasons for their adoption in some cases. The maximum tractive effort of an electric locomotive can be sustained at speeds two or more times those at which the steam locomotive can sustain its maximum effort and while the electric machine is only limited by the power

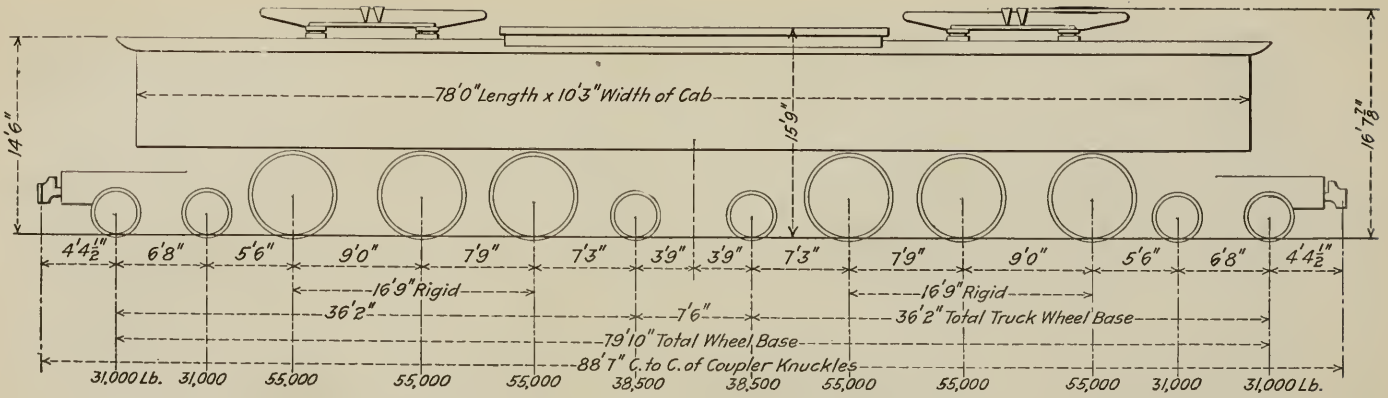


FIG. 33—Outline of a Type of Electric Locomotive Designed for Passenger Service over Heavy Mountain Grades.

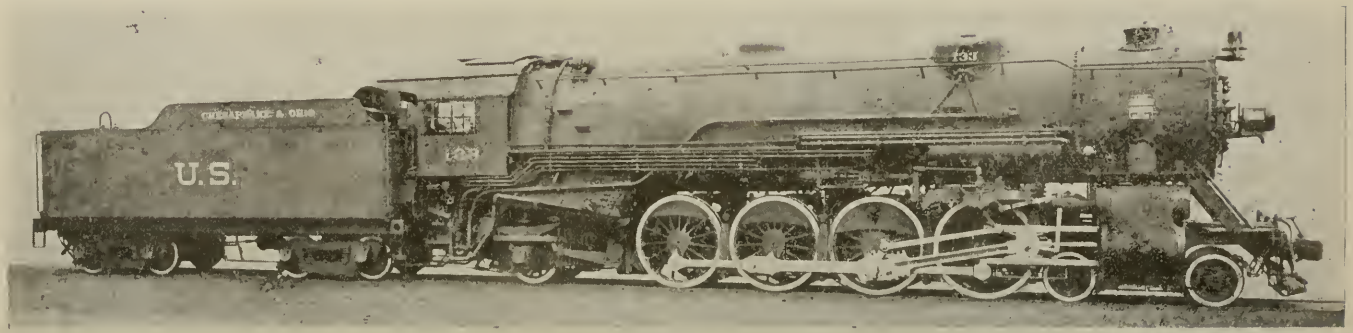


FIG. 32—A Steam Locomotive of Modern Design, Adapted to Heavy Passenger Service, Particularly on Mountain Divisions.

lost as heat in the motors, the maximum power possible of development by the steam locomotive is a fixed quantity.

Comparison of a Steam with an Electric Locomotive.—In order that a clearer understanding may be had concerning what has been covered in a foregoing discussion, an actual comparison has been made of the tractive effort and the horsepower of a steam and an electric locomotive of equal weights,

TABLE I.—MECHANICAL CHARACTERISTICS OF STEAM AND ELECTRIC LOCOMOTIVES FOR HEAVY MOUNTAIN SERVICE

Characteristics	Steam	Electric
Whyte's Classification	4-8-2	4-6-2 — 2-6-4
Weight—Engine and tender	273.75 tons	266 tons
Weight—Engine only	352,000 lb.	532,000 lb.
Weight—Engine on drivers	243,000 lb.	330,000 lb.
Number of pairs of drivers	4	6
Weight per pair	60,750 lb.	55,000 lb.
Wheel diameter, inches	69	68
Total wheel-base, engine and tender	75 ft. 8.5 in.	79 ft. 10 in.
Maximum tractive effort	58,200 lb.	110,000 lb.
Maximum horsepower	2,825	5,860
Continuous horsepower	2,825	3,200

both designed for heavy passenger service over mountain grades. The selection of these particular locomotives was also based on the idea of showing rather the performances that are typical of what is possible of accomplishment in the respective fields, than what is possible with particular types of locomotives. The curves of other types would have the same general outline even though corresponding values would be higher or lower according to the specific type of locomotive. The comparative data concerning weights, etc., is given in Table 1.

The steam locomotive—Fig. 32—is of modern design, embodying arch tubes and superheater and is designed to carry a boiler pressure of 200 lb. which in conjunction with cylinders of 28-in. diameter and 20-in. stroke, results in the very large rated tractive effort of 58,000 lb.

The electric locomotive is a representative type built for heavy passenger service in a mountain region. The arrangement of driving wheels, etc., is shown in Fig. 33 and the operating characteristics, in Fig. 37.

The first comparison to be made is that of tractive effort. Curves showing the relation between speed and tractive effort

for both locomotives are shown in Fig. 35. The maximum tractive effort of the steam locomotive is 58,000 lb., while that of the electric is 110,000 lb. Reference to the data in Table I shows that the weight on the drivers is 330,000 lb., so that the 110,000 lb. tractive effort for starting is based on 30 per cent adhesion, a very conservative value for the electric locomotive. This maximum tractive effort in the case of the electric locomotive is maintained until a speed of 20 miles an hour is reached, while the steam locomotive cannot maintain

Gauge of track	4 ft. 8½ in.
Tractive power, maximum	58,200 lb.
Factor of adhesion	4 18
Cylinders:	
Diameter	28 in.
Stroke	30 in.
Weight in working order:	
Leading	51,500 lb.
Driving	243,000 lb.
Trailing	57,500 lb.
Engine	352,000 lb.
Tender	193,700 lb.
Wheel bases:	
Driving	18 ft. 3 in.
Engine	40 ft. 0 in.
Total engine and tender	75 ft. 8½ in.
Wheel, diameter, driving	69 in.
Boiler:	
Inside diameter	84½ in.
Pressure	200 lb.
Grate area	76.3 sq. ft.
Fuel	Soft coal
Firebox, length and width	114½ in. by 96¼ in.
Tubes, number and diameter	247—2¼ in. 45—5½ in.
Length	20 ft. 6 in.
Heating surfaces:	
Tubes	2,970 sq. ft.
Flues	1,323 sq. ft.
Firebox	335 sq. ft.
Arch Tubes	34 sq. ft.
Total	4,662 sq. ft.
Superheater	1,085 sq. ft.

FIG. 34—Data Applying to the Locomotive Illustrated in Fig. 32.

its maximum beyond 10 miles an hour. The electric locomotive curve begins to drop rapidly at 20 miles an hour and at 38 miles an hour both locomotives have the same tractive effort.

To give a better idea of what the high tractive effort of the electric locomotive means, a curve has been drawn—Fig.35—

showing what the tractive effort would be for two steam locomotives operating as a double-header. The dotted curve is slightly higher for the maximum tractive effort but in practical operation the single electric locomotive could start the

TABLE II.—TRACTIVE EFFORT AND HORSEPOWER DATA —ELECTRIC LOCOMOTIVE

Speed (m.p.h.)	Tractive Effort	Horsepower
0—20	110,000	5,860
23	95,000	5,800
25	75,000	5,000
27	60,000	4,320
29	50,000	3,870
32	40,000	3,420
40	24,000	2,560
50	14,500	1,960
60	10,000	1,600

same train as the two steam locomotives, and would have an advantage over them up to a speed of 24 miles an hour. When it is considered that on heavy-passenger mountain

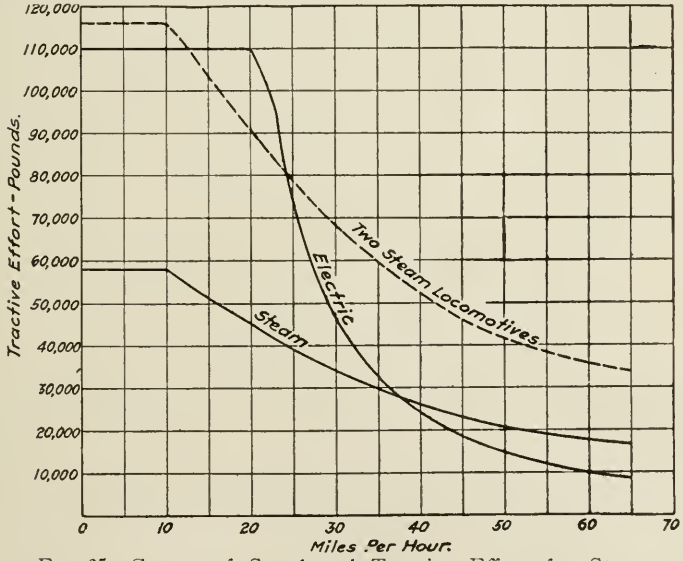


FIG. 35—Curves of Speed and Tractive Effort for Steam and Electric Locomotives.

service, speeds do not greatly exceed this figure, it becomes clear that the electric locomotive is nearly equivalent to the two steam locomotives. It must be remembered, however,

that the two steam locomotives could maintain this speed continuously while exerting a tractive effort of 80,000 lb., but the electric locomotive could not, on account of the fact that the motors would require a current much above the continuous rating.

Since horsepower is an important factor, curves have been drawn—Fig. 36— showing the relative horsepower for the two locomotives chosen. Here the comparison is even more striking, and the advantage possessed by the electrical loco-

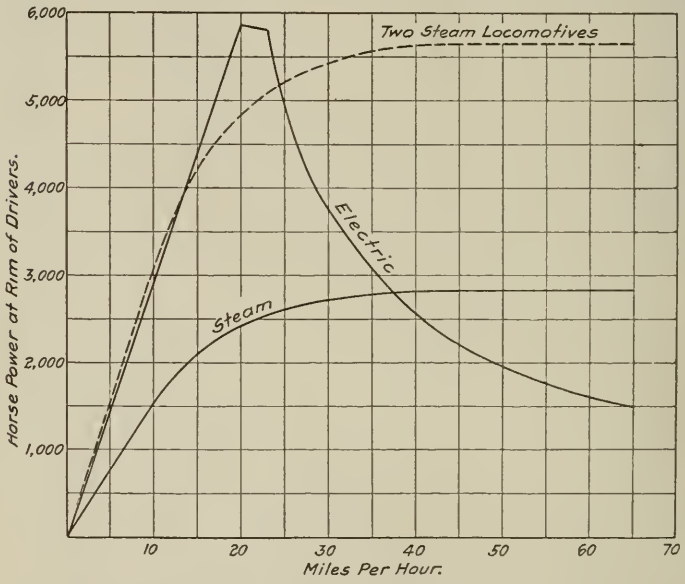


FIG. 36—Curves of Horsepower Developed by Steam Locomotives and by Electric Locomotives.

motive is easily recognized. Although the electric locomotive has the same weight as the steam, its maximum developed horsepower at the rims of the drivers is 5,860 hp. as compared to 2,825 hp. for the steam locomotive, and when compared with two steam locomotives it shows, for the working range, the ability to deliver the equivalent in horsepower. Of course, the continuous rating must not be overlooked; for the electric locomotive this is 3,200 hp. The increase in horsepower is due to the increased speed for the same tractive effort.

The significance of the curves shown in Fig. 35 may be further illustrated by the example of a passenger train which

requires at certain sections or grades, a tractive effort varying from 50,000 lb. to 30,000 lb. At 50,000 lb., the speed of the steam locomotive would be 16½ miles an hour; the electric, 29 miles an hour, or nearly double. At 40,000 lb. the steam locomotive would be moving at the rate of 24.5 miles an hour; the electric, 32 miles an hour.

The characteristic curves—Fig. 37—for the electric locomotive were obtained by actual test. From these curves the tractive effort at any speed can be read off directly, Table II,

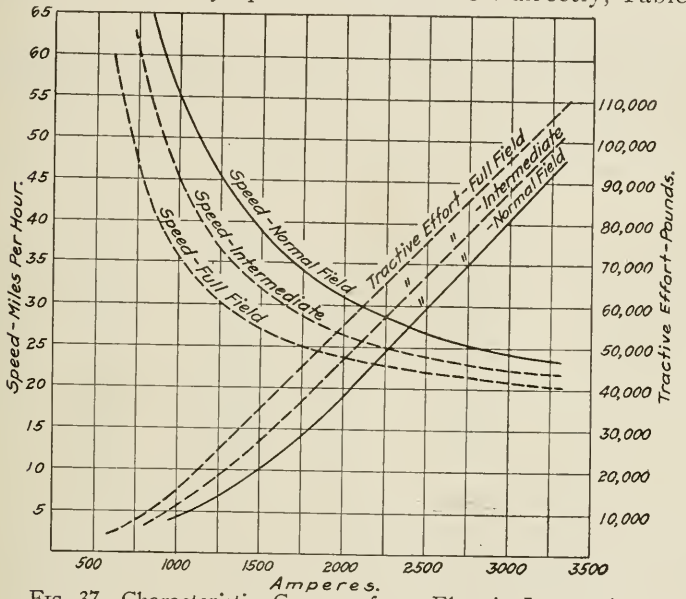


Fig. 37—Characteristic Curves of an Electric Locomotive.

and thus is obtained the data which, in turn, was used to plot the tractive effort curves in Fig. 35. Applying the formula,

$$\text{H.P.} = \frac{\text{tractive effort} \times \text{speed}}{375}$$

and using the first two columns of Table II, the third column —horsepower rating—was obtained for use in plotting the curve of horsepower in Fig. 36.

In the set of characteristic curves—Fig. 37—for the electric locomotive, it is to be noted that there are three speed curves and three corresponding tractive-effort curves. This type

locomotive uses "field control," thus resistance losses are reduced. The tractive-effort and horsepower curves cover the normal-field condition. To show briefly what is gained with this field control, an example in which the continuous horsepower rating is 3,200 hp., may be taken. With normal field this corresponds to a speed of 34 miles an hour and a tractive effort of 35,000 lb. If a greater tractive effort is necessary continuously, the speed can be reduced. By operating on full field, a speed of 24.5 miles per hour is obtained with a tractive effort of 49,000 lb.

The data for plotting the curves of tractive effort and horsepower for the steam locomotive was obtained by calculating

TABLE III.—TRACTIVE EFFORT AND HORSEPOWER DATA —STEAM LOCOMOTIVE

Speed m.p.h.	Piston Speed Ft. per Min.	Speed Factor	Tractive Effort	% of Max. H.P.	H.P.
0	...	....	58,000	...	0
10.3	250	1.000	58,000	55.6	1,570
12	292	.954	55,300	64.3	1,820
15	365	.897	52,000	73.1	2,070
20	487	.784	45,500	85.6	2,420
25	610	.675	39,100	92.3	2,610
35	852	.515	29,900	98.3	2,780
41	1,000	.445	27,000	100.0	2,825
45	1,095	.405	23,500	100.0	2,825
55	1,340	.332	19,250	100.0	2,825
65	1,580	.281	16,300	100.0	2,825

the piston speed in feet per minute, and applying percentages which are used by locomotive builders and correspond to the various piston speeds. This data is shown in Table III.

CHAPTER XIII

METHODS USED FOR ACCELERATING ELECTRIC LOCOMOTIVES

In locomotive operation where heavy trains are handled it is necessary to have a uniform rate of acceleration from start to maximum speed. The longer the train the more important this factor becomes, owing to the strength of the surges, which may result in serious damage to couplers and draft gears.

Direct-Current Locomotive Control.—To anyone who has ridden in electric cars or trains the variation in the operation as far as smoothness is concerned, is noticeable. In the case of the trolley car for instance, the smoothness of acceleration depends on the skill of the motorman as the control equipment is manually operated, there being no automatic features to regulate the maximum amount of current. The case of the electric locomotive is similar; it has been the universal practice to consider the master controller as the throttle and to let the engineman regulate the amount of power, the amount consumed being indicated by electrical instruments provided for this purpose. The control apparatus is more elaborate than that used on the trolley cars or on elevated railway trains, but in general, the same fundamental electrical principles are involved.

The arrangement of resistances and motor combinations as generally used today is the result of several years of operation. There are many schemes of connections, all of which are feasible, yet have certain disadvantages. The importance of the subject makes it advisable to take up and discuss these various schemes.

Subway and elevated railway trains use automatic regulation so that the rate of acceleration does not depend on the

movement of the master controller but is taken care of automatically by a relay, set for some definite motor-current value. While some of these trains operate very smoothly throughout the entire range of the control from start to full speed, other trains using equipment of a different and older type will show very decidedly the changes in speed. The latter trains will operate smoothly up to about 15 miles an hour, then there will be a moment when the speed will not increase but will perhaps even decrease slightly and then acceleration will again take place smoothly to maximum speed. The effect of these changes is extremely noticeable, and while it is possible to operate elevated or subway trains in this manner, the only result being discomfort to the passengers, it would be impossible on account of the damage caused by the surge, to allow this variation in speed in the case of the electric locomotive.

The reason for this variation is found in the method used for changing the motor combination so as to increase the speed. The latest method and one that is necessary in electric locomotive operation is known as the bridging method. Other methods, namely, the shunting method and the open-circuit method have been used, however, for elevated, subway, and surface cars. Each of these methods will be discussed so that the subject of motor and resistance combinations will be clearly understood, although all of the schemes do not necessarily apply to the electric locomotive.

Full voltage cannot be applied directly to the motors at rest, as the current through them would be so great as to cause serious damage both electrically and mechanically. The motor then offers only its ohmic resistance to the current so that sufficient other resistance must be placed in series with the motors to give the proper amount for starting. At the first control point approximately 90 per cent of the voltage is absorbed by the resistance; cutting-out the resistance step by step increases the voltage at the motor terminals until full voltage is obtained.

Rheostatic Control—Series Resistance.—There are several ways of connecting the resistance. The easiest way and one which requires the least amount of control apparatus, is to connect the motors permanently according to the full-speed

combination desired and then provide sufficient resistance. When all of the resistance is cut-out, the motors are in the final arrangement and there are no combinations of motors in the series and parallel. This arrangement is known as rheostatic control.

With rheostatic control the resistances may be connected in three ways, known respectively as series resistance, parallel resistance, and series-parallel resistance. Series resistance signifies that all of the resistance in the circuit is first placed in series with the motors and then is gradually short-circuited by sections until the motors are connected across the full trolley voltage. The switches for short-circuiting the sections of the resistance are all open when the power is first applied,

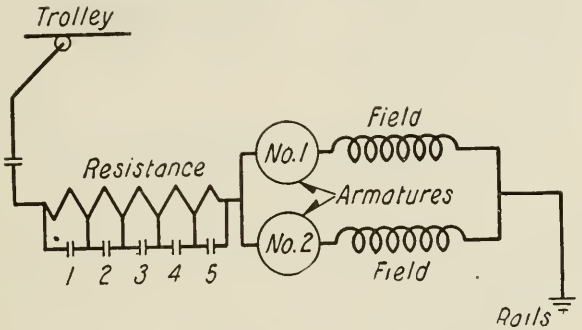


Fig 38—Connections When a Series Resistance is Used for Starting

and are closed consecutively. A diagram of this arrangement is shown in Fig. 38.

Rheostatic Control—Parallel Resistance.—In the case of rheostatic control using parallel resistance, the resistance steps as well as the motors, are connected in parallel. At starting, only one high-resistance unit, designed to keep the current value normal, is in circuit. As acceleration takes place, additional resistors are connected in parallel with the initial resistance until, on the last step, the entire resistance is short-circuited. As each step of resistance is placed in circuit, combined resistance is less, so that the voltage to the motors, and hence the current, is increased—see Chapter III—according to the law of parallel resistance.

The number of parallel resistances required depends on the

value of each, but the joint resistance at the last step must be low enough so that when the entire resistance is short-circuited the increase in voltage to the motors will not be greater than the amount necessary for smooth acceleration.

The arrangement of connections is shown in Fig. 39. The

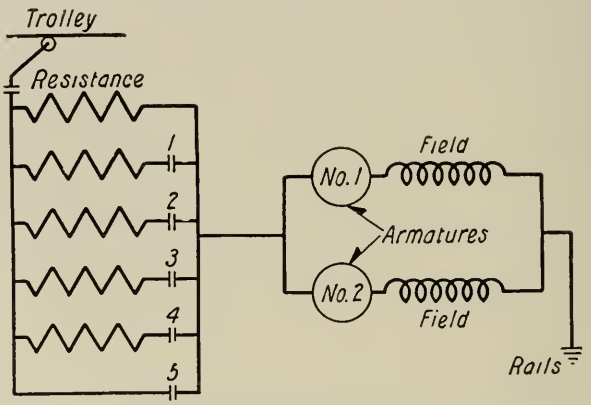


Fig. 39—Connections When Resistances in Parallel Are Used for Starting.

switches, 1, 2, 3, 4, 5, are all open at the start, the current passing through the top resistance when the trolley switch is

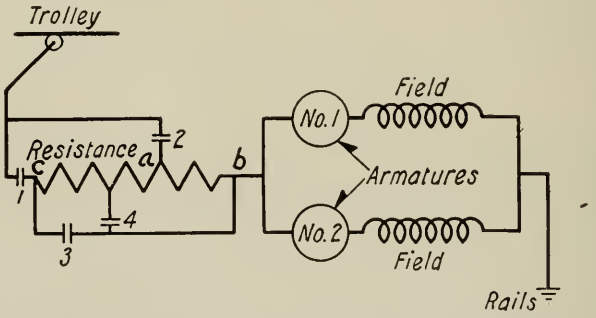


Fig. 40—Connections for Using Combined Series and Parallel Resistances for Starting.

closed. The switches are closed consecutively and when No. 5 is closed, the motors are operating on full trolley voltage.

Rheostatic Control—Combination Resistance.—The third class of arrangement for the starting resistance, is a combination of the other two. The diagram of connections is

shown in Fig. 40. The switches are shown as Nos. 1, 2, 3, and 4, respectively. On the first step switch No. 1 is closed and all the resistance is in series; on the next step switch No. 2 is closed and No. 1 is opened, so that part of the resistance has been cut out, leaving section *ab* in the circuit; switch No. 3 is closed next and No. 2 still remains closed. The section of the resistance *ca*, cut out by the closing of switch No. 2, is brought back into the circuit by closing the switch No. 3, but instead of being in series it is in parallel so that the joint resistance is less. On the next step, switch No. 4 closes and No. 3 opens,

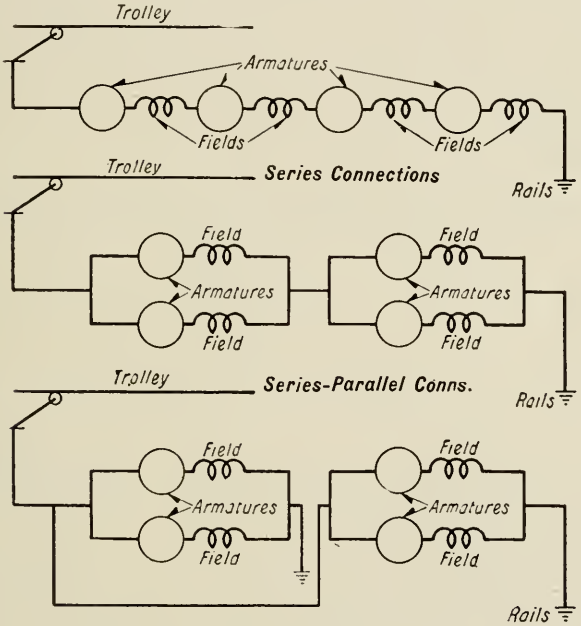


Fig. 41—Motor Combinations for Starting.

so that the joint resistance is again reduced. The last step cuts out all of the resistance by the closing of switches No. 1 and No. 3.

Motor Combinations.—While with the three arrangements described, smooth operation is obtained, there is a decided objection to the system of connections as they are not economical from the standpoint of power consumption. There is considerable power lost in the resistance, and greater economy

can be obtained by connecting the motors in combinations, instead of permanently, as less resistance is required and therefore the loss due to this cause is less. When motors are to be used in combinations, complete equipments include an even number of motors. For locomotive work the minimum number is generally four and may be as high as design permits, although the locomotives operating out of the Pennsylvania Terminal, New York, have only two motors. To gain the maximum saving in power consumption the combinations are as shown in Fig. 41, the motors being connected first in series, then in series-parallel, and finally all in parallel.

On small locomotives of 60 to 80 tons or less, the first or series arrangement with the four motors in series, is generally eliminated so that the locomotive starts with the motors

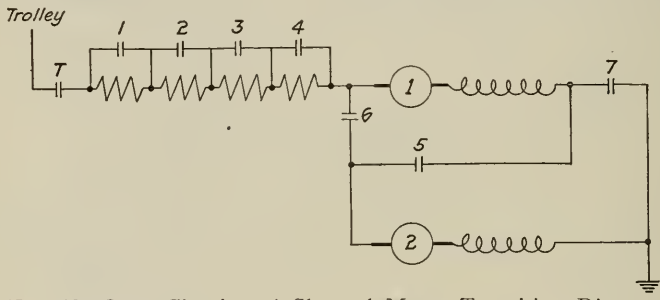


Fig. 42—Open Circuit and Shunted Motor Transition Diagram

in the series-parallel arrangement. With four-motor equipments, two motors are connected permanently in parallel and are controlled as one unit.

When combinations of motors are used, the problem of changing from one to the other, while obtaining smooth acceleration is somewhat different than with series resistance as explained for Figs. 38, 39 and 40. With rheostatic control the circuits are simple; all that is necessary is to arrange the circuits as shown by the diagrams and provide a means for cutting out the resistance. With the motor combinations, however, means for making the transition from series to parallel must be provided.

Transition Methods.—There are three methods used in changing the motors from series to parallel, namely: the open

circuit method, the shunted motor method, and the bridging method. These three methods are listed in the chronological order in which they were developed; the bridging method is the latest developed and the smoothest in operation, while the open circuit method was the first and the roughest. The further information might be added, that the development of the transition methods did not occur in connection with the development of electric locomotives, but with that of elevated and subway multiple-unit trains as well as with certain types of trolley cars.

Open-Circuit Transition.—With the open-circuit method—shown in Fig. 42—the connections between the motors and the trolley are broken during the transition step. The motors, therefore, are developing no torque during the short time required for changing the circuits, and they are in parallel when the trolley connection again is made. While the change is being made, the speed decreases and there is a surge when the motors again receive current. The switches closed for full series operation would be T, also 1, 2, 3, 4 and 5; to bring the two motors in parallel, switch, T, is opened and then switch No. 5, after which switches No. 6 and No. 7 are closed, followed by switch T, with the correct amount of resistance in series. Because of its tendency to cause surges, this arrangement or method would not be satisfactory for locomotive operation.

Shunted-Motor Transition.—The same diagram—Fig. 42—may be used to show the shunted-motor method of control. The full-series circuits are the same as those for the corresponding point in the open-circuit arrangement. Then, instead of opening the switch, T, and cutting off the power, this switch is left closed and part of the resistance is again cut-in by the opening of switches No. 2, No. 3 and No. 4. An instant later switch No. 7 is closed and connects the No. 1 motor directly to ground, at the same time creating a shunt around the No. 2 motor by this short circuit to the ground. Switch No. 5 is then opened and switch No. 6 is closed, which connects the No. 2 motor in parallel with the No. 1 motor, and then the resistance is again cut out step by step so that the motors are finally left in full parallel. This method has a dis-

tinct advantage over the open-circuit method in that only one-half instead of all of the torque is lost during transition.

Bridging Transition.—The bridging method is different from the other two, as it does not require the current to be cut off from either motor, nor is either motor short-circuited or shunted. This feature gives this method an advantage over both of the others, in that the motors continue to work all the time and the torque is constant during the transition period. Smooth operation is thus obtained throughout the whole period of acceleration.

The arrangement of the circuits is as shown in Fig. 43. The line switches, LS, are connected between the trolley or source of supply and the other switches and motors. The resistance

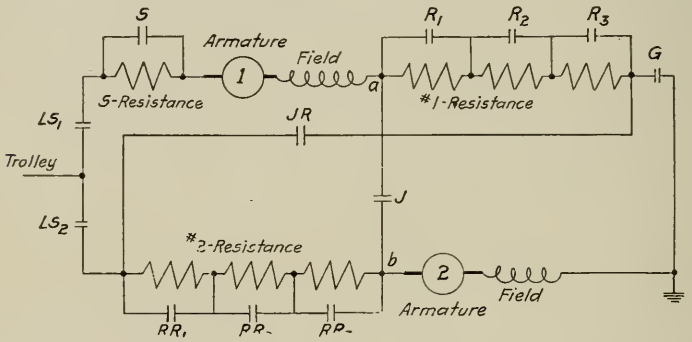


Fig. 43—Diagram of Connections for Bridging Transition.

which switch, S, cuts out, is used only with the motors in series, and is generally short circuited at the second notch of the controller, when the switch, S, closes. The resistance switches, R_1, R_2, R_3 and RR_1, RR_2, and RR_3, are used to disconnect in steps, the total resistance. The switch, JR, when closed, connects the two motors in series outside of the two sets of equal resistances; the switch, J, when closed, completes a jumper, connecting the two motors directly together, the resistance being left out of the circuit.

The sequence of switches is as follows: On the first step the switches LS, and JR are closed, so that the motors are in series themselves also with all of the resistance. The current passes through LS_1, S-Resistance, No. 1 motor, No. 1 Resistance, through the switch, JR, No. 2 Resistance, No. 2 motor, to ground. On the next step, switch, S, closes and the motors

begin to pick-up. The switches R_1, RR_1, R_2, RR_2, R_3, and RR_3 are closed consecutively, and switch J, is closed, as the controller is turned from notch to notch. After the switch J, is closed, all of the resistance switches for the No. 1 and No. 2 resistances open, which leaves the motors in series, and the current passes through switches LS_1, S, and J.

The bridging is next arranged. Switches LS_2 and G, are closed, and complete a circuit from the trolley through LS_2, No. 2 resistance switch, J, No. 1 Resistance, and G, to the ground. There are thus established two circuits through the switch, J, through which the current tends to pass in opposite directions. The resistances, however, are of such a value that when placed across the line, the current will be the same as that taken by the motor circuit at the speed of the locomotive when the change is made from series to parallel. If the two currents are equal there will be no current passing through J, and it can be opened without notice. Of course it is practically impossible to have the switch J, open at the exact time when the current is zero. The current flowing through the motors and through the switch J, in the direction *a* to *b*, will depend on the speed of the locomotive. The back electromotive force of the motors increases with the speed and the current is reduced. On the other hand, the current through the resistances in series is always the same. Therefore, if the engineman waits too long before proceeding to parallel, the current through the resistance will be greater and the switch, J, on opening, will break a current flowing from *b* to *a*. If the speed is too low the extra current will flow from *a* to *b*. The opening of the switch J, establishes two parallel circuits, each of which contains one motor and its resistance in series. The resistance switches are closed progressively as in the series position, except that corresponding switches in each set of resistance close together, as, for example, R_1 and RR_1. With the bridging method, the motors, when started, are connected in series with the resistance and are brought up to full parallel without having, at any time, the torque changed more than the amount due to the cutting-out of one resistance step.

High-Voltage Direct-Current Locomotive Control.—In general, the direct-current locomotives operating on direct current at 1,200 to 3,000 volts, may be regarded as using the same

motor combinations as those operating on 600 volts, when it is considered that two or more motors are grouped together as one unit.

As the voltage on the overhead wire increases it becomes necessary to keep two or more motors in series across the line voltage at all times, due to the fact that it is not commercially possible to design a single armature for operation with direct current at a voltage higher than 1,500 volts.

As explained in a previous chapter the railway motor rotates at a speed such that its counter electromotive force is nearly equal to the impressed voltage, and as the voltage across the motor terminals increases, it becomes more difficult to secure this result. It is a simple matter, however, to insulate the conductors for the high voltage so that by combining the motors in groups the counter electromotive force required of each motor is reduced to a normal value, and the operation is satisfactory.

The experience gained from the use of 3000-volt electric locomotives on the Chicago, Milwaukee and St. Paul is an example. The equipment of the original locomotives includes 1500-volt motors, two of these motors being permanently connected together and considered as a single unit, as far as the control arrangement is concerned. The later locomotives have a larger number of motors so that at high speed three motors are connected together across the 3000 volts. There are only 1000 volts across the terminals of each of the motors, so that each one then is in reality a 1000-volt motor insulated for 3000 volts.

Alternating-Current Locomotive Control.—The locomotive control for alternating-current operation is entirely different from that of direct-current operation. In the first place, the voltage on the overhead wire is comparatively high—from 11,000 to 15,000 volts—and cannot be connected directly to the motors, so that means must be provided for reducing this voltage to a workable value. This reduction is accomplished by means of transformers.

A further difference between the two systems of operation is found in the fact that, instead of a single type, there are three types of alternating-current electric locomotives,

namely, the single-phase, the three-phase, and the split-phase.

In the case of the single-phase locomotive it is not necessary to connect the motors in different combinations to regulate the voltage and thus increase the speed. The motors can be connected permanently in parallel and the voltage increased by connecting to different taps, or leads, on the transformer, each lead giving an increase in voltage, and hence an increase

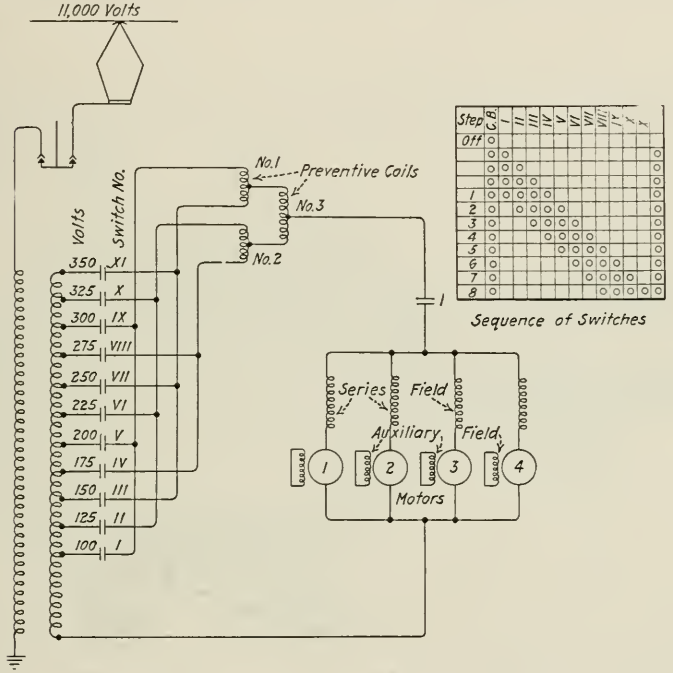


FIG. 44—Schematic Diagram of Main Circuit and Sequence of Switches—Single-Phase Alternating-Current Locomotive.

in speed. By means of these taps the power can be applied to the locomotive gradually and smooth acceleration obtained.

Single-Phase Arrangement.—A schematic diagram for the main circuits of a single-phase electric locomotive, is shown in Fig. 44. The transformer, which is of the double-coil type, has its primary connected between the trolley, at 11,000 volts, and the ground. The secondary of the transformer has eleven taps, which are connected to switches marked from I to XI. These taps, after passing through the switches, connect to four

leads running to the preventive coils, every fourth tap connecting to the same lead. From the preventive coils, one lead is used as a feeder for all four motors, these being connected permanently in parallel.

To show just what takes place and how the voltage is increased a sequence of switches is shown. The first running position is when the first four switches are closed. By tracing the path of the current through these four switches, it is

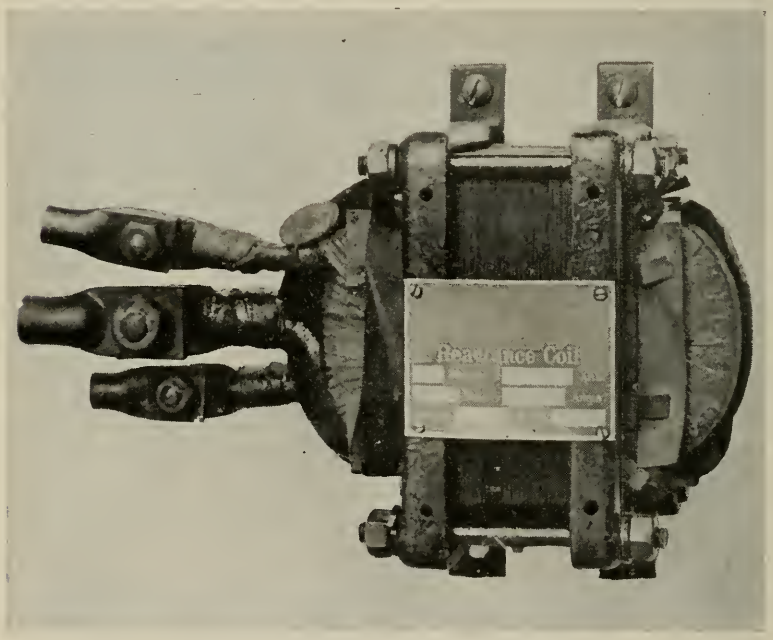


Fig. 45—A Reactance Coil Complete.

found that switches I and III connect across coil No. 1 and switches II and IV across coil No. 2. These two coils are then connected together by the large coil No. 3, from which is taken one tap. It would be impossible to connect leads I and III directly together as the difference in voltage—50 volts—would result in a severe short circuit. The same condition applies with leads II and IV, but by interposing coils No. 1 and No. 2 the short circuit is avoided. By connecting the coil No. 3, as

shown, the four different voltages are reduced into one, which is the mean of the sum of four voltages. Therefore, on step No. 1, the voltage to the motors is 137.5 volts. On step No. 2 the switch I opens and V closes so that the voltage across the motors becomes 162.5 volts. This procedure is continued until full speed is reached, the arrangement of taps and switches being such that smooth acceleration is obtained throughout the range from start to full speed.

Preventive Coils.—The nature of locomotive work requires that current should be supplied to the motors continuously and that open circuits shall not occur between points on the controller. It is, therefore, necessary to be able to pass from one tap to another on the transformer, without open-circuiting, which means that both taps must be closed at the same time. The preventive coil performs this function also. It would be possible—and is done, in many cases—to have a fewer number than four transformer switches closed at one time. The advantage of having four lies in the fact that since these four switches carry the total current to the motor, each switch is only carrying one-fourth. Thus the size of switch required can be reduced.

These preventive coils are wound so that a short circuit is prevented between the taps connected at different voltages, but they offer very little impedance and resistance to the current taken by the motor. They are made—see Fig. 45—of a few turns of copper strap, surrounded by iron, and resemble a small transformer. The two halves of the coils are wound so that in the case of a short circuit, the coils are added together and offer a large amount of impedance and inductance, but when only the main motor-current is passing through, the windings neutralize each other so that very little impedance is offered, and thus flexibility of control is obtained at high operating efficiency.

Three-Phase and Split-Phase Arrangement.—Both three-phase and split-phase locomotives are equipped with three-phase motors. Motors of this type have a constant speed, which depends on the frequency of the supply circuit and not on the voltage. In bringing the locomotive up to this constant speed a resistance must be inserted in the secondary winding to keep the current down to a normal value. As the locomo-

tive accelerates, this resistance is cut out step by step, until it is entirely out and the secondary winding is short-circuited on itself.

In the case of large locomotives the amount of resistance, if of the grid type, is very bulky. This space requirement is reduced on the split-phase locomotives of the Norfolk & Western by the use of water rheostats, which also provide a very flexible arrangement.

CHAPTER XIV

ENERGY LOSSES INCURRED BY THE VARIOUS METHODS OF ACCELERATION

The previous chapter described the different methods used to increase gradually the voltage to the motors, by the manipulation of resistances. The different motor arrangements, also the different methods used to change from series to parallel, were discussed and it was shown how, with the bridging method of transition, the motors may be brought from

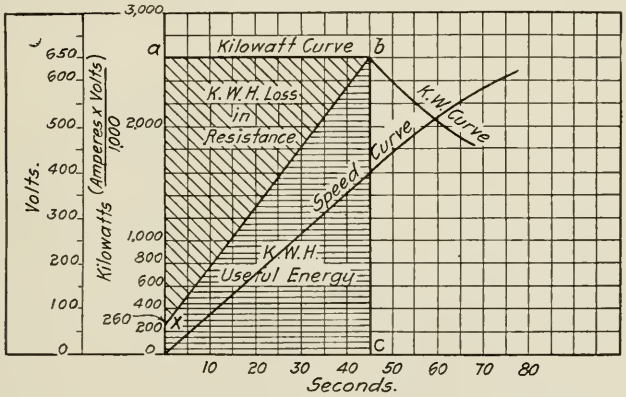


FIG. 46—Energy Consumption and Resistance Losses—Rheostatic Control.

start to full parallel without interruption in the tractive effort.

In describing rheostatic control, mention was made of the fact that this arrangement is not economical, that the resistance loss is excessive, but that this can be reduced by connecting the motors in combinations. It is impossible to avoid rheostatic losses entirely, but they can be considerably reduced. The saving in power that can be made by connecting the motors in combinations can be shown by a concrete example.

Assume that a locomotive is equipped with four motors and

operates from a third rail at 650 volts. It requires 1000 amperes per motor to start this locomotive and accelerate it to a certain speed—where all the resistance is cut out—in 45 seconds, when coupled to a certain train.

Energy Losses—Rheostatic Control.—A rheostatic arrangement, where all the motors are connected in parallel and where a series resistance is used will be considered first. The energy lost in the resistance with this arrangement is shown in Fig. 46. Each motor takes 1,000 amperes at 650 volts, so that the locomotive is taking from the power supply, 650 volts $\times$ (1,000 $\times$ 4) amperes = 2,600,000 watts, or 2,600 kilowatts. This amount of power is consumed during the straight-line acceleration, and is represented by the line *ab*, the resistance being meanwhile cut out step by step. During this straight-line acceleration 45 seconds elapse, so that the energy consumed is represented by the area, *oabc*, and is 2,600 kw. $\times$ 45 sec. = 117,000 kw. seconds or

$$\frac{\text{117,000 kw seconds}}{\text{3,600 (no. of sec. per hr.)}} = \text{32.5 kw-hrs. (which is the input)}$$

The amount of energy lost in the resistance depends on the product of the current and the difference between the line volts and the motor volts. At any instant, it is equal to the current value at that instant, multiplied by the difference between the line voltage and the motor voltage. A certain voltage is necessary to start the motors, and in figuring, this is taken as 10 per cent of the line voltage. In our present problem 65 volts would then be required and the kilowatts taken by the motors is:

$$\frac{65 \times 4000}{1000} = 260 \text{ kw.}$$

which is shown at point *x* in Fig. 46. At the end of 45 seconds all of the resistance has been cut out and the motors are consuming all of the energy, at the full voltage—650 volts—of the line. The line *xb*, therefore represents the volts across the motor and also the dividing line between the energy lost in the resistance and that used by the motors. As has just been

stated, the resistance loss is the current $\times$ (line volts—motor volts), so that the area above the line *xb* represents the energy lost in the resistance and the area below the line, the useful energy absorbed by the motors. Since 10 per cent of the line voltage is taken by the motors at start, 90 per cent. of the voltage will be lost in the resistance at start. The average voltage loss, since *xb* is a straight line, will be half of this or 45 per cent of the line voltage, in this case, 45 per cent of 650 volts or 292.5 volts. The same current—4,000 amperes—flows through the resistance so that the energy loss is:

$$\frac{4000 \text{ amperes} \times 292.5 \text{ volts} \times 45 \text{ seconds}}{1000 \times 3600} = 14.63 \text{ kw-hrs.}$$

The average voltage used by the motors necessarily will be 55 per cent of 650 volts, or 357.5 volts. The useful energy then is

$$\frac{4000 \times 357.5 \times 45}{3600 \times 1000} = 17.9 \text{ kw-hrs.}$$

Energy Loss Series-Parallel Control.—The series-parallel arrangement where there are two sets of two motors each, connected permanently in parallel, will be considered next.

In starting, the two sets are connected in series, but instead of 4,000 amperes—the current used by the same equipment and rheostatic control—being taken from the line, only 2,000 will be used, although each motor receives 1,000 amperes and the locomotive develops the same drawbar pull. At transition the motors are connected four in parallel and 4,000 amperes is again taken from the line.

With the motors connected according to the series-parallel arrangement, two motors are in series across the line. As before, each motor requires its 10 per cent voltage to start, or 65 volts, with a current of 1,000 amperes, so that the voltage used by the motors is 130 volts. There is then 520 volts, or only 80 per cent, to be absorbed by resistance. At starting the current—2,000 amperes—from the line is one-half of that required with rheostatic control, so that the useful energy is of the same value, namely, 260 kw., and point *x* is located as

shown in Fig. 47. The time required to accelerate is the same as before, namely, 45 seconds, so that the line *xg* will be the dividing line between the energy loss in the resistance and the useful energy absorbed by the motors, and corresponds to and is located the same as line *xb*, in Fig. 46.

The average voltage loss during series is one-half of the 80 per cent, or 40 per cent of the line volts, or 260 volts. In order to ascertain the kilowatt-hours loss during series, it is necessary to know at what time the motors will reach full series. The total time is divided between series and parallel in the ratios of the counter electromotive forces of the motors

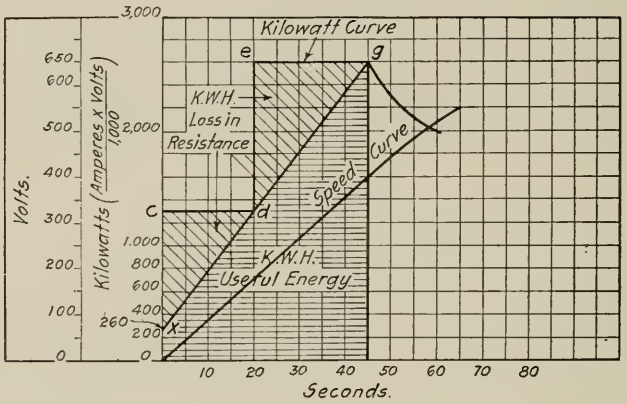


Fig. 47—Energy Consumption and Resistance Losses—Series-Parallel Control.

in series and in parallel, after the resistance is cut out. When the two motors are in series each has one-half of 650 volts, or 325 volts across the terminals. According to the assumption for this motor, 65 volts is sufficient to give 1,000 amperes through the motor, so that when running without resistance and consuming 1,000 amperes, the back e.m.f. must be the difference between 325 and 65, or 260 volts. When the motors are in parallel, each motor has 650 volts across the terminals, but the voltage corresponding to 1,000 amperes is still 65 volts. The counter e.m.f. must then be the difference between 650 and 65 or 585 volts. The ratio of 260 to 585 is 0.444. This means that 44.4 per cent of the acceleration time is consumed while the motors are in series and 55.6 per cent of the time

in parallel. The number of seconds in this problem for the series operation is 44.4 per cent of 45 or 20 seconds. It has been shown that the average voltage is 260 volts, so that the kilowatt-hours energy loss in the resistance while the motors are in series is:

$$\frac{260 \text{ volts} \times 2000 \text{ amperes} \times 20 \text{ seconds}}{3600 \times 1000} = 2.89 \text{ kw-hrs.}$$

When the motors are first connected in parallel the voltage across each motor is, of course, one-half of the line voltage, or 325 volts, the resistance taking care of the other 50 per cent. This loss in the resistance of 50 per cent is reduced to zero when all the resistance is cut out. The average loss in parallel is then 25 per cent or 162.5 volts. The time in parallel is 55.6 per cent or 25 seconds—see preceding paragraph—so that the loss in parallel measured in kilowatt-hours is

$$\frac{162.5 \text{ volts} \times 4000 \text{ amps.} \times 25 \text{ seconds}}{3600 \times 1000} = 4.51 \text{ kw-hrs.}$$

and the total loss in the resistance is

$$2.89 + 4.51 = 7.40 \text{ kw-hrs.}$$

The useful energy for the motors has not changed, but remains the same or 17.9 kw-hrs. (See discussion of Rheostatic Control.) The total input then is

$$17.9 + 7.40 = 25.30 \text{ kw-hrs.}$$

which shows a saving in the total energy input of approximately 25 per cent when compared with rheostatic control.

Energy Loss—Series, Series-Parallel, Parallel Control.—A further reduction in the total energy consumed by the resistance can be obtained if the motors are connected first, four in series, then series-parallel, and finally all in parallel. With the four motors in series 40 per cent of the voltage is taken by the motors in series so that only 60 per cent, or 300 volts, will be lost in the resistance. The average voltage loss during the time the four motors are in series is half of 60 per cent or

30 per cent of the line voltage, and amounts to 195 volts.

The time factor is obtained as before and is the ratio of the back e.m.f. of the motors when operating without resistance and at the voltages. The back e.m.f. of the motors when connected four in series is

$$\frac{650 \text{ volts}}{4} - 65 \text{ volts} = 97.5 \text{ volts}$$

The back e.m.f. of the motors when in parallel is, as shown before, 585 volts. The ratio of 97.5 to 585 is 0.166. This means that for 16.6 per cent. of the acceleration time, the four

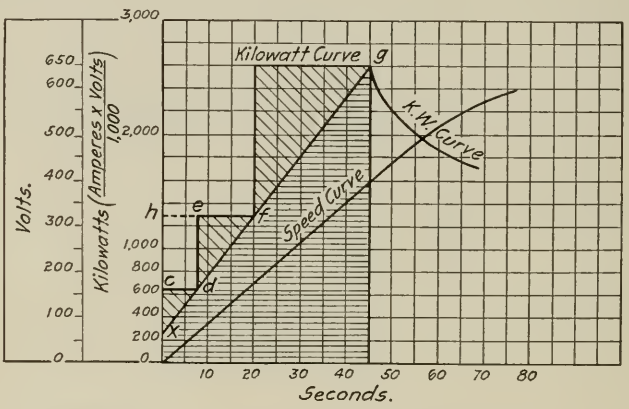


Fig. 48—Energy Consumption and Resistance Losses. Series, Series-Parallel, Parallel Control.

motors are in series. In this particular case, where 45 seconds is the total time, the elapsed time of series operation is 7.5 seconds.

The total energy at start is 1,000 amperes $\times$ 650 volts $=$ 650 kw.; in Fig. 48 it is the line *cd*. The saving in energy or saving in loss in the resistance by connecting the four motors in series as the first combination is equal to the area *cdeh*, and is equivalent to

$$\frac{7.5 \text{ seconds} \times 650 \text{ kw.}}{3600} = 1.35 \text{ kw-hrs.}$$

Therefore the total loss in the resistance is the difference between 7.40 and 1.35, or 6.05 kw.-hrs., and the total energy

input will be the difference between 25.30 and 1.35, or 23.95 kw.-hrs.

Energy Consumption and Resistance Losses.—The summary of the foregoing calculations is as follows:

Arrangement	Total Energy Input	Loss in Resistance
Rheostatic	32.5 kw.-hrs.	14.63 kw.-hrs.
Series-Parallel	25.30 "	7.40 "
Series, Series-Parallel, Parallel	23.95 "	6.05 "

Formulas.—The foregoing results have been worked out for a specific problem, but since definite percentages of time are required to reach the transition points it is possible to make use of formulas so that any problem can be worked out rapidly without going through all of the calculations just explained. These formulas are as follows:

Let A = accelerating or starting current per motor.
" V = trolley voltage.
" T = time in seconds to reach speed with all resistance cut out and motors in full parallel.
" W = watt-seconds taken from the line.
" W/R = watt-seconds lost in resistance.
" W/M = watt-seconds used by motors.

Then for Rheostatic Control

$W = 4\ A\ V\ T.$
$W/R = 4\ A \times 0.45 \times T = 1.8\ A\ V\ T.$
$W/M = W - W/R = 2.2\ A\ V\ T.$

For Series-Parallel Control

$W = (2\ A\ V \times 0.444\ T) + (4\ A\ V \times 0.556\ T) = 3.112\ A\ V\ T.$
$W/R = (2\ A \times 0.4\ V \times 0.444\ T) + (4\ A \times 0.25\ V \times 0.556\ T) = 0.911\ A\ V\ T.$
$W/M = W - W/R = 2.2\ A\ V\ T.$

For Series, Series-Parallel, Parallel Control

$W = (A\ V \times 0.166\ T) + (2\ A\ V \times 0.278\ T) + (4\ A\ V \times 0.556\ T) = 2.945\ A\ V\ T.$
$W/R = 0.911\ A\ V\ T - 0.166\ A\ V\ T = 0.745\ A\ V\ T.$
$W/M = W - W/R = 2.2\ A\ V\ T.$

These formulas cover a four-motor equipment; for two-motor equipments the values are one-half.

Notching Diagram.—For the purpose of constructing the diagrams in Figs. 46, 47, and 48, it was assumed that the cur-

rent, hence the watts input, was constant and that the voltage at the motors varied uniformly. For general calculations this assumption is correct, as the average values can be assumed. Actually, however, there is a variation in the current. When a resistance step is cut out the current increases, as additional voltage is applied to the motor. With the increase in voltage the speed of the motor becomes greater, the counter electromotive force increases, and the current becomes less. How the current and the voltage change at the motors as the control is operated, is shown approximately, in Fig. 49,

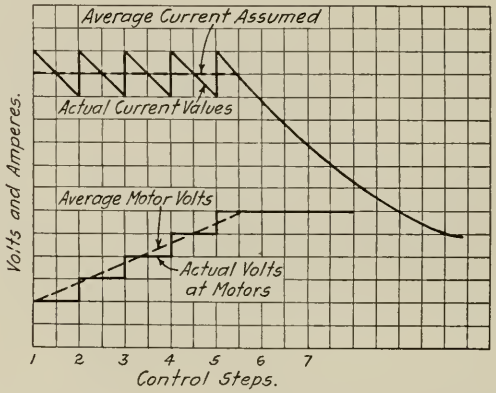


Fig. 49—Changes in Current and Voltage at the Motors as the Control is Operated.

which also illustrates the effect of rheostatic control, but the same features are true of the other motor arrangements. The curves in Figs. 46, 47, and 48 show values in kilowatts, and for exact calculations should be drawn in the same manner as the curve of current in Fig. 49. The line voltage is constant so that the watts vary as the current, the curve of which—Fig. 49—represents also the kilowatt curve.

Field Control.—There is another method of reducing still further the amount of energy lost in the resistance and thus obtaining more efficient operation. This method utilizes what is known as field control, which regulates the speed of the motor by varying the number of effective field turns. This arrangement is particularly desirable for electric locomotives,

and has been applied to the a.c-d.c. passenger locomotives in use on the N. Y., N. H. & H. The Pennsylvania locomotives operating into New York City also have field control.

The field control motor has two sets of field windings. In large motors these windings are separate, but in smaller motors there may be only one set of field coils with a tap, so that if connection is made to the tap lead only a part of the field turns will be used.

When starting the motor, the entire field is in the circuit and will have extra strength due to the extra turns of wire around the poles so that for the same acceleration, i.e., the same tractive effort, the current required is less than with the other

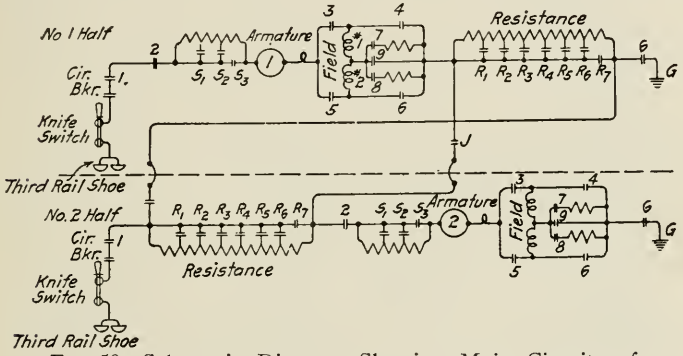


Fig. 50—Schematic Diagram Showing Main Circuits of a Locomotive on Which Field Control is Used.

methods of control just explained, less current being required to give the same ampere-turns and hence field strength.

In the case of a series motor the field strength determines the speed, the effect of the stronger or full field being to lower the speed. Lower current means a reduction in the resistance losses, and a slower speed means that the resistance is cut out sooner, which also reduces the losses.

To get a field-control motor up to the same speed as a motor without field-control, some of the field turns are cut out of the circuit, the field is weakened and thus the motor speeds up. This change to the short field is made without incurring main resistance losses.

An important advantage of field-control is that many economical running speeds are available. With the series-parallel

arrangement of motors, for four-motor locomotives, there are normally only two running speeds—series and parallel—but with field-control motors there would be four speeds, two in series and two in parallel. One of the series speeds would be obtained with the motors running on the full field and the other, with the motors running on the short field. The same is true for the two speeds in parallel.

As previously mentioned, the Pennsylvania electric locomotives operating into the New York City terminal are a good

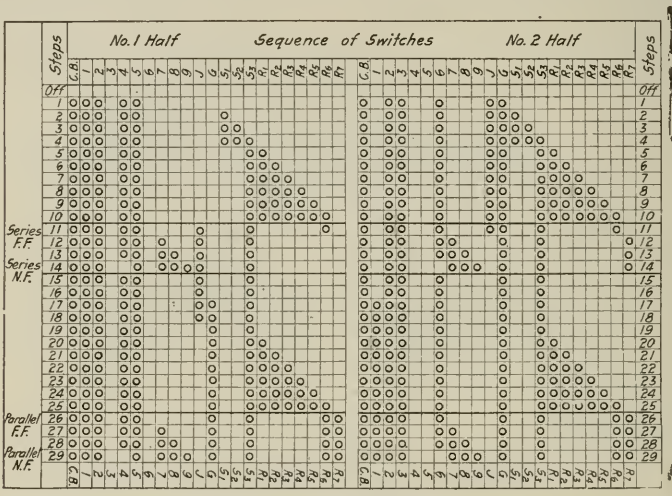


FIG. 51—Sequence of Switches for Diagram of Connections Shown in Fig. 50.

example of what can be accomplished by the use of field-control.

The change from full field to short field is made in three steps. For the first two steps there is resistance in parallel with the field, shunting away some of the current and thus weakening it; the third step disconnects half of the field. During acceleration the energy saved by the field control is 45 per cent of that which would be consumed if field control were not used. Moreover, from full field to short field when the locomotive is exerting approximately 20,000 lb. drawbar pull, the speed increases by as much as 37 per cent.

A schematic diagram of the main circuits of the locomotive, together with the sequence of switches is shown in Figs. 50

and 51. The arrangement is nearly as simple as the diagram used in the previous chapter to illustrate the bridging method of control; there are a few more resistance steps and the added feature of field control.

The field variation is obtained—see Fig. 50—for the No. 1 motor by closing switches Nos. 7, 8, and 9. The other four switches of the field group, namely, Nos. 3, 4, 5, and 6, are to regulate the direction of the current through the fields and hence the direction of rotation of the motor. When switches No. 3 and No. 6 are closed, the current pases through the No. 1 and No. 2 field coils in one direction, and in the opposite direction if switches No. 4 and No. 5 are closed.

Assuming that switches No. 3 and No. 6 are closed, field control is obtained in the following manner. First, switch No. 7

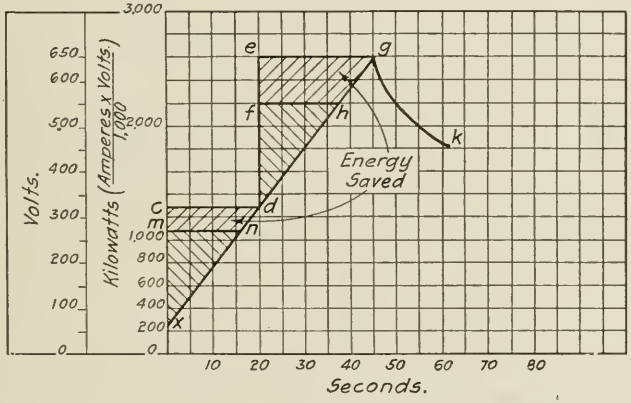


Fig. 52—Energy Consumption and Rheostatic Losses—Field Control.

closes and a resistance which shunts away from field of motor No. 2 part of the current which has passed through field of motor No. 1 is connected in the circuit. The total field strength is therefore weakened and the locomotive gains speed. Switch No. 8, by which more current is shunted away from the field of motor No. 2, closes next, followed by the closing of switch No. 9, which cuts out the field of motor No. 2 entirely.

As previously mentioned, the saving due to field control results from the fact that less resistance is required, and also a

lower current during acceleration. The curve *c d e g k*—Fig. 52—is the kilowatt curve of the locomotive without field-control, and is identical with the corresponding curve in Fig. 47. When field control is used, the kilowatt curve for series operation is *mn*, instead of *cd*; and in parallel operation *fh*, instead of *eg*. The complete curve with field control is then *m n d f h g k;* the saving of energy is represented by the areas indicated.

Energy Losses—High-Voltage Direct Current.—All of the preceding discussion has dealt with locomotives using direct current at 600 volts. In general, the same holds true for the high-voltage direct-current locomotives, and calculation can be made in the same way. Resistance is used according to the same general arrangements, and while the motors are permanently grouped, the individual groups are considered as one unit, and are connected in series and in parallel.

Energy Losses—Alternating Current.—As shown in Fig. 44, no resistance is used with the single-phase locomotive so that there can be no rheostatic losses. There are, however, some losses in the transformer and in the preventive coils.

In the case of the three-phase and the split-phase locomotives, resistance is used in the secondary winding and hence there are rheostatic losses. There is no connection between the secondary and primary, but the losses in the secondary, nevertheless, represent power input which is expended in the primary but merely supplies the rheostatic losses in the secondary instead of doing useful work. The motors are permanently connected in parallel so that the energy losses are, in general, similar to direct-current losses when the motors are permanently connected in parallel.

CHAPTER XV

REGENERATIVE BRAKING WITH ELECTRIC LOCOMOTIVES

The hauling of freight over the heavy grades of mountain divisions is a class of service in which the electric locomotive has an important advantage and one which cannot be realized by the steam locomotive. This advantage is due to the fact that the electric locomotive makes use of regeneration, and delivers to the line, energy which is available when a train descends a grade, and which, with steam operation, is dissipated as heat at the brake shoes. The delivery of this energy to the electrical conductor, helps to supply power to other trains so that the demand upon the main power station is less than would be the case without regeneration.

Available Energy on Grades.—Considerable energy is available when a heavy freight train or passenger train is running down grade. It may be assumed, for example, that a 3000-ton train is running down a 2 per cent grade at the rate of 14 miles per hour. The horsepower available can be calculated in the following way. For each 1 per cent grade the down-pull along the grade is 20 lb. per ton—see Grade Resistance, Chapter XI—so that on a 2 per cent grade there will be 40 lb. per ton, minus the friction of the train, which, in this case, may be assumed as 6 lb. per ton. There is then a net amount of 34 lb. per ton. Since the internal friction is greater, the grade-pull of the locomotive would be proportionately less, a fair allowance being 40 lb. minus 15 lb., or 25 lb. With a 3000-ton train made up of a 3000-ton trailing load and a 250-ton locomotive, the total grade-pull would be

$$\begin{aligned} 3000 \times 34 &= 102{,}000 \text{ lb.} \\ 250 \times 25 &= \quad 6{,}250 \text{ lb.} \\ &\overline{\quad\quad\quad\quad} \\ &108{,}250 \text{ lb.} \end{aligned}$$

The speed in feet per minute at 14 miles per hour is 1232, so

that the horsepower to be dissipated at the brakeshoes as heat, or else is available for regeneration is

$$\frac{108{,}250 \times 1232}{33{,}000} = 4041 \text{ hp.}$$

Returning electric power to the conductor or line means that electric power is actually generated on the locomotive or, in other words, the mechanical horsepower developed on the down-grade is converted into electrical watts. To accomplish this, the electric motors, which normally supply the motive power for the propulsion of the train are used as generators. Since the motors on the electric locomotive are always connected to the axles by gearing, side rods, or a combination of both, these motors revolve at all times with the revolution of the drivers. If the mechanical and electrical efficiencies are neglected, the transformation of power takes place according to the relation, 746 watts equal 1 horsepower. A method is provided for controlling the amount of electrical power returned, so that this electrical power can be kept constant or can be varied to absorb the amount of energy available on the grade which the train is descending. This regulation makes it possible—within limits—to absorb this kinetic energy of the train and to regenerate sufficient power so that the speed of the train down the grade is under perfect control without the use of air brakes, which can be held in reserve either for an emergency or for stopping the train.

While, in general, regeneration is the same for all systems, in that it provides a means for retardation of the train and for supplying power to the line, still there is some difference. In order to understand what takes place it may be well to review some of the fundamental principles of the electric motor, and to consider the subject of regeneration under two different headings, namely: first, regeneration with direct-current motors or with single-phase series variable-speed motors, and, second, with three-phase or constant-speed motors.

Direct-Current Regeneration.—In the case of a direct-current application, it will be assumed that the motors are of the series, commutating type, this design of motor having the proper characteristics for general railway work.

The series motor, as previously described—Chapter VI—

gets its name from the arrangement of the connections between the armature and the field, these two parts of the motor being connected in series, so that the same current which passes through the armature also passes through the field coils. The connections are shown in Fig. 53. The path taken by the current causes the strength of the field to vary with the armature or load current, so that both the speed and the torque of the motor are affected. The pull, or torque, being represented by the product of the field strength multiplied by the armature current—Chapter VI—increases rapidly with the increasing current which results when the speed is decreased.

In order to regenerate with the direct-current system, the voltage generated by the motors must be greater than the voltage or pressure on the electrical conductor, and this gen-

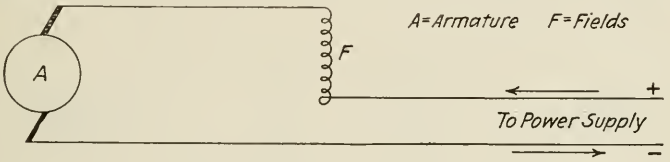


FIG. 53—Diagram of Series Connections for Armature and Field of Series Motor.

erated pressure must be under control. The conditions to be met are analogous to those found when the attempt is made to force water into a pipe which is already under pressure; a greater pressure must be used to overcome this pressure in the pipe. The motors must therefore become, for the time being, electric generators. While it is true that if the fields are reversed, a series motor can be made to generate current and act in the capacity of a generator, operation under this condition is very unstable, so that it is necessary to make certain changes in the motor connections in order to control satisfactorily, the voltage generated; there are certain vital conditions which must be met and overcome.

Controlling apparatus must be provided so as to take care of variable conditions which are met in the direct-current system. For instance, the line voltage at a locomotive which is regenerating, may suddenly be reduced, due to heavy trains starting up in the immediate vicinity. Under these conditions with a certain voltage being generated by the motors, the re-

generated current will immediately increase. With the motors connected as series motors, this immediately will increase the field strength, which in turn will cause the regenerated current to increase so that an excessive overload will be thrown on the entire equipment.

On the other hand, if the line voltage should rise after a certain stable voltage existed on the motors, then the difference between them would be less, and result in a decrease of regenerated current. The field excitation would, therefore, be decreased and a further decrease in current would result and possibly the regenerated current might be reduced to zero. If this condition persisted still further, there would be excessive current in the opposite direction and serious difficulties would result. In fact, these changes could happen so quickly

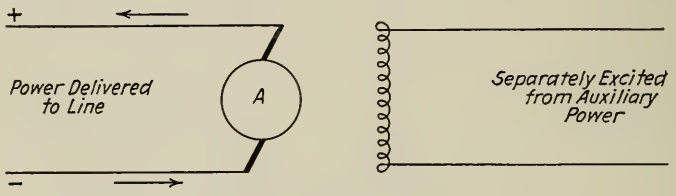


FIG. 54—Diagram of Connections for Armature and Field of Shunt Motors.

and frequently that the time element of relays and controlling apparatus could hardly be made sensitive enough to properly safeguard and yet be effective.

The question, therefore, becomes one of separating the fields from the armature, and exciting the fields of the motor from some separate source, as shown in Fig. 54. The main fields of the d.c. motors consist of a very few turns, having low resistance, so that it would be impossible to excite these fields from the main voltage supply, as the excitation would be too great for the voltage desired. Instead of series generators, therefore, the motors are used as shunt generators, and by adjusting and controlling the amount of current in the separately excited field, the strength of the field and the number of lines of force are so regulated that sufficient voltage can be generated in the armature to force current into the line against the line voltage.

There are many methods possible in connection with this

separate excitation. The fields can be separately excited from some source such as a storage battery, but a better and more practical arrangement is to furnish this power from a motor-generator set. Any scheme, to be effective, must be automatic within limits so as to secure motor stability and weaken the field when the regenerated current increases, due to a momentary drop in the line voltage. The equipment must also be operative under reverse conditions wherein the line voltage increases.

After this separation of the field from the armature, the motor—now used as a generator—is no longer the self-contained and automatic unit which it is when operating as a motor, under which condition, the field strength and the armature current are always equal or in proportion to each other, and the operation of the motor automatically, is stable.

When operating as the generator the conditions are entirely different. The field strength is no longer in proportion to the armature strength; when the motor is running at high speed, a very low field excitation is all that is necessary to give the desired voltage for regeneration, and there exists a certain distortion of the armature flux. The torque, however, which this motor, operating as a generator, exerts during the absorption of the mechanical energy of the train is proportional to the product of the armature current and the field strength. It also follows that at high speed with the low field strength, the armature current must be relatively large in comparison to the field, and this results in distortion of the armature flux, as previously mentioned. With the elaborate system of control on the locomotives, it is possible to make use of the starting resistances, etc., and reverse the operations that take place when accelerating the train, and when operating at high speed the armature current can be kept within certain limits proportional to the field strength. Under these conditions it may be recognized that the braking effort or retardation is not at a maximum value, but as the speed of the train is reduced, then retardation can be gradualy increased.

In view of these conditions it can be clearly seen that a means must be provided for the prevention of undue surges of armature current. When the change is made to regeneration, the excitation must be such that upon connecting the motors

to the line, as generators, the voltage is approximately equal to the line voltage. Moreover, mechanical conditions such as differences in the air gaps of the motors, diameters of driving wheels, etc., which will result in different characteristics of the individual generators, must be anticipated and arranged for, so that the load will be proportionately divided between the various motors. The automatic regenerating control must also be such that the regeneration effort will not be too quickly applied.

All of these conditions have been met by the electrical engineers and successful regeneration braking has been accom-

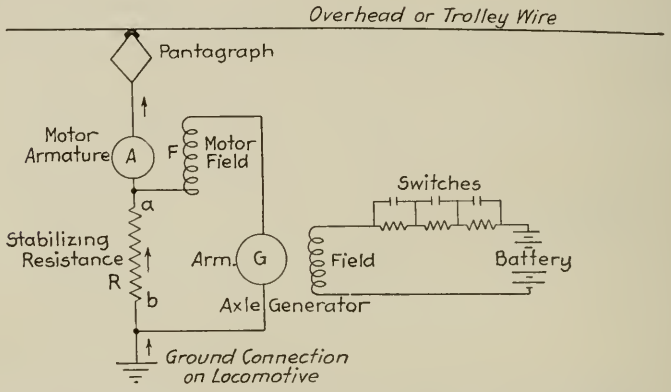


Fig. 55—Connections for Direct-Current Regeneration System Using Stabilizing Resistance and Axle-Driven Generator.

plished for direct-current electric locomotives, with a minimum amount of excess apparatus, additional complications being practically negligible.

Regenerative braking is in use on the passenger locomotives of the Chicago, Milwaukee & St. Paul. A stabilizing resistance is used, and causes the field current in the motor—acting as a generator—to vary inversely as the regenerated current so that sudden changes in line voltage do not affect the motor, and it is thus protected. The excitation current for the motor fields during regeneration is not supplied by a motor-generator set, but by a generator driven from one of the axles of the leading truck.

The use of the stabilizing resistance and axle-driven generator has advantages over other schemes, and deserves ex-

planation. The connections when regenerating are shown in Fig. 55. When the motor is regenerating, current is then passing through the motor armature, A, into the line, and in order to have a complete circuit, an equal current must flow back from the rails, through the ground connection, then through the stabilizing resistance to the motor armature. With this regenerated current there is a certain IR, or voltage drop, in the stabilizing resistance. It will also be noted from the diagram—Fig. 55—that the armature of the axle generator is not connected directly to the motor field, F, but that the stabilizing resistance, R, is also in the circuit. The excitation of the axle-driven generator is sufficient under these conditions to generate voltage in the armature, G, such that there will be enough current through F to give proper voltage for regenerating. The amount of current in this circuit depends on the voltage of G, the resistance of the motor field, F, and the IR drop in the resistance.

The action of the automatic feature may be described by explaining what occurs when the line voltage suddenly drops. Immediately the motor armature, A, delivers more regenerated current and this increased current returning through the stabilizing resistance increases the IR drop, or, in other words, the voltage across *ab* is increased. Since the voltage from G has not been changed, the current through the motor field must be decreased, and with the decreased excitation the voltage across the armature, A, must decrease and the regenerated current, therefore, decreases also. The reverse is also true. If the voltage suddenly rises, the regenerated current becomes weaker, the IR drop across the resistance, R, is reduced, so that the current in the field, F, and the motor voltage increase and tend to maintain the regeneration. The operation is automatic and the motors are protected.

Whenever the speed of the locomotive increases, due to a change in grade, the voltage of the axle generator increases and the excitation of the main field, F, is strengthened. This will increase the regenerated current, but the IR drop also will increase and the excitation will be reduced, until a new balanced speed is set up automatically.

If a locomotive's equipment includes four or more motors, a wide variation of speed during regeneration can be obtained

by combining the motors according to parallel and series connections which are reversed as compared to the manner in which these connections are used when the locomotive is pulling. For instance, during acceleration, the motors of the locomotive are operated in combination, starting, in the case of the four-motor equipment, with the four motors in series, then changing to two motors in parallel and these two parallel sets in series, and finally changing to four motors in parallel. Three running speeds are thus possible with these combinations. In the case of a freight locomotive, the usual rates are 8 miles an hour, with four motors in series, 16 miles an hour with the second arrangement, and 32 miles an hour with all four motors in parallel.

When regenerating with a locomotive running at a speed of approximately 32 miles an hour, the motors would be used as four in parallel, and when the train speed had decreased to 16 miles an hour the combination would be changed to that with two motors in parallel and two in series, and when a further reduction in speed takes place, the motors would be connected four in series. The reason for changing the combination is that, as the speed of the train decreases, the control must be such as to allow more current to pass through the fields of the motors. In this way, the principle that a certain number of lines of force must be cut during a certain time to generate a given voltage, is applied, and the voltage of the motors is kept higher than the line voltage. The reduction in speed reduces the rate of cutting these lines of force, so that it is necessary to increase the number of lines in order that the total number of lines which are cut will continue to remain the same.

There is a limit to the lowest speed, below which point it is not possible to keep up the field strength, hence the voltage becomes less than the line voltage and regeneration stops unless the motors are put into the second combination, when two motors are in series, the voltages being added together to force current against the line voltage. In the final arrangement under regeneration, namely, with four motors in series, all four voltages are added together to oppose the line voltage. The arrangement is analogous to a water system, where there

is a double-acting pump or compressor, and the air pressure or water pressure obtained from the first section of the system passes into a high-pressure cylinder, where the pressure is increased to a higher amount, by the movement of the second piston.

Single-Phase Regeneration.—Regeneration with the single-phase series commutating-motor system, is possible and it is interesting to see just how this is accomplished. The single-phase system uses a higher voltage for the overhead wire, usually 11,000 volts. Transformers are used on the locomotive to reduce this high voltage to a voltage suitable for the

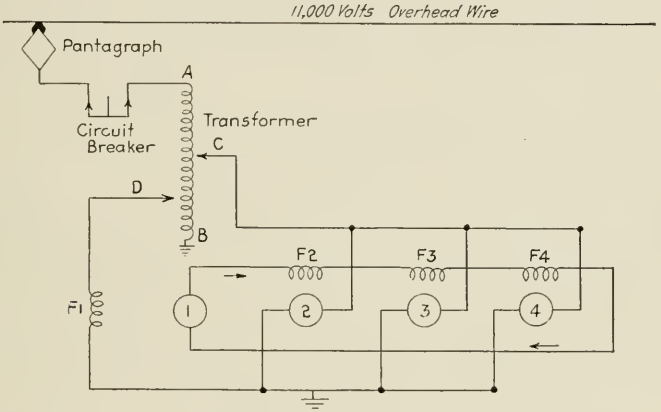


Fig. 56—Diagrammatic Connections for Regeneration with Single-Phase Locomotive.

operation of the motors, taps being taken out at the proper voltages.

A diagrammatic sketch of the connections used for regeneration with a single-phase, series, commutator-type of locomotive is shown in Fig. 56. If 11,000 volts is applied at the lead, A, of the transformer which is represented by the loops as shown, a small amount of current, known as exciting current, will pass through the coils and out at the lead B, which is connected to the ground. If it were possible to measure, beginning at lead, A, the voltage throughout all of the turns of the transformer, it would be found that there is a decrease in voltage as progress is made along the coils from A toward B until zero voltage is obtained at B. Thus it is possible to get

any desired value of voltage by connecting to the coil at the proper point, a cable which can be brought out of the transformer case. This cable is known as a tap.

For the supply of excitation current, a motor-generator set can be used as explained for the direct-current arrangement, but another satisfactory arrangement for alternating-current single-phase operation is one in which one motor of the four on the locomotive is used as a generator for furnishing current to excite the fields of the other three, only the latter, delivering power to the line. As shown in the diagram, motor No. 1 is used as a generator and furnishes current to the fields F_2, F_3, and F_4. The corresponding armatures generate current which passes to the transformer through the lead, C.

As the speed of the locomotive decreases, the voltage from the motors can always be kept at a sufficient value to regenerate by strengthening the current to the field of these motors. This is accomplished by increasing the strength of the field of the No. 1 motor by connecting the lead, D, to a suitable voltage tap either higher or lower. Moreover, it is possible to get additional variation by moving the lead, C, to a higher or lower tap. As a result of these adjustments, the regenerated voltage can be maintained slightly above the line voltage over a wide range of train speeds. For convenience, the transformer has been shown as an auto-transformer, one end, A, of which is connected to the 11,000 volts and the other, B, to the ground. With a certain voltage at C, generated by the motors Nos. 2, 3 and 4, the voltage can be increased at A, according to the ratio $\frac{AB}{CD}$.

In the cases of both the direct-current and the single-phase systems, the inherent working principle is the maintenance of a voltage or electrical pressure at the regenerating machine, higher than that of the distributing system to which it is connected. If the voltage of the distributing system could be kept constant, regeneration with direct current would be simplified. But in railway service there are varying conditions, due to the movement of trains and the variation in grades and curves, and although regeneration with direct current works most satisfactorily, the locomotives driven by three-phase mo-

tors are generally considered superior, as far as simplicity is concerned.

Regeneration with Three-Phase Motors.—Before going into the details of regeneration with three-phase motors, it may be well to review some of the principles of these motors.

The polyphase motor is a constant-speed type and its speed does not depend upon the voltage of the circuit but upon the frequency, and for a given frequency there is a certain motor speed known as the synchronous speed.

The stationary winding of an induction motor is continuous on the inside of the motor frame, and the armature has no connection whatsoever with the stationary winding or with the power supply circuit, the latter being connected only to the stationary winding. The magnetic field which is produced by the alternating current in the stator, rotates—see Chapter VIII—at a speed depending upon the frequency of the supply circuit and upon the number of poles of the motor. A current which tends to stop the rotation of the field is induced in the armature and as the rotating field cannot stop, the armature, or rotor, is dragged along at practically the same speed, there being a slight slip, depending upon the load or the work which the motor is doing. When the rotor is running in exact step with the rotation of the field in the stationary winding, or stator, it then is revolving at what is known as its synchronous speed.

When regeneration takes place the rotor runs at a speed slightly above the synchronous speed of the stator field. For this reason and also because the electrical supply is still connected to the primary winding of the stator, the rotor conductors overtake and therefore cut the lines of force of the revolving stator field, and current is generated in the rotor winding in a direction opposite to that taken when the motor does not exceed synchronous speed. The rotor flux created by the reverse current flowing in the rotor, affects the flux in the primary or stator windings and generates in them a flux to oppose rotation. The reversal of the flux in the primary causes a reversal of the primary current and hence power is delivered to the line. At the same time, the action of the rotor flux tends to bring the rotor speed back to that of the magnetic

field and therefore offers a resistance which supplies the breaking effort necessary to retard the locomotive when operating on a grade.

To simplify this explanation, a simple illustration of the primary and secondary circuits of a transformer is shown in Fig. 57. The secondary —rotor—is connected to a motor and the primary—stator—to the supply line. When the motor is loaded, current passes through the secondary winding and a flux is set up which opposes the flux generated in the iron core by the primary current, and additional high-tension current is necessary in order to overcome the secondary flux. If the motor is made a generator and sufficiently speeded-up, the

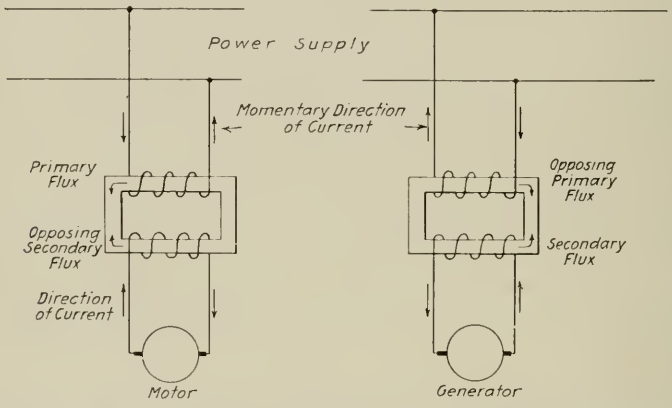


Fig. 57—Two Transformer Diagrams Showing Relations Between Current and Core-Flux. Analogus to Three-Phase Induction Motor When Driven Above Synchronous Speed.

current will be reversed in the secondary winding, the secondary flux also will be reversed, and a primary flux will be set up to oppose this secondary flux. In order to set up this opposing flux in the primary, a reversal of current is necessary and hence power is put back into the line supply. Tests show that practically as much power or torque is required to run the motor a given number of revolutions per minute above the synchronous speed as the force which the motor will overcome when it is running as a motor at the same number of revolutions below the synchronous speed. The question is not one of generating a voltage to overcome

the trolley voltage, as in the case of the direct-current system, but is purely one of speed of rotation. Operation is automatic without any change in the motor circuit. It therefore follows that no appreciable variation in the speed with regeneration, takes place when using three-phase motors. In fact, it is the general practice, to leave on the power when the train starts on the down grade and when the speed tends to be higher than that corresponding to the synchronous speed of the motors, regeneration occurs automatically, and the locomotive then begins to deliver power to the line.

The use of a phase-converter in the locomotive to enable the three-phase motor to operate from a single overhead trolley or a single-phase supply, does not in any way change the automatic feature when regenerative breaking equipment is applied to locomotives of this type.

Advantages of Regeneration.—The many advantages gained by the use of the regeneration principle are important, and can be classified as regards their effect upon brake shoe and wheel wear, upon maintenance and wear of the air brake and draft gear equipment, economy of power supply, and the speed, safety and uniformity of train operation.

The energy which a heavy freight train possesses while descending a grade, is large, and with only air brakes available, this energy must be dissipated as heat at the brakeshoes. Rapid wear of the shoes results, and the wheels also are subjected to heavy wear and overheating, with the risk of loose and broken tires. When regeneration is used in this class of service, the elimination of practically all of this dissipation of heat results in reduced maintenance cost for the wheels and brakeshoes.

The air brakes, brake rigging, and draft gear are subjected to severe strains, when only the brakes can be used for descending grades, so that regeneration results in a reduction of maintenance.

Regeneration results in a saving of horsepower output required of the power house, depending, of course, upon operating conditions and the grades encountered. The saving in power consumption may reach 10 to 15 per cent in ordinary service over mountain grades.

The speed of a heavy train on a down-grade is often limited

by the permissible heating of the brakeshoes, but with the use of regeneration, a speed which is the safe speed for the track, curves and construction of the roadbed, is allowable. This rate is usually higher than is permissible when only the brakes can be used.

Safety of operation is one of the most important advantages of regeneration. The train is under better control and possible accidents resulting from loose tires, are eliminated.

In train service the results obtained from regeneration are more uniform operation of the longer trains which are adopted as the transportation system grows, and expands.

CHAPTER XVI

THE AIR BRAKE EQUIPMENT FOR THE ELECTRIC LOCOMOTIVE

It is not the purpose of this chapter to describe in detail the operation and construction of the air brake. In general the air brake equipment for electric locomotives is just the same as that used on modern steam locomotives, there being only a few slight modifications. However, since steam is not usually available in sufficient quantity, the air pressure must be obtained from an electrically-driven air compressor. This feature will be described in some detail.

Changes Necessary for Electric Locomotives.—The practice for the steam locomotive is to use only one brake valve and the distributing valve is located in close proximity to it, but the arangement is somewhat different on the electric locomotive. In the first place two brake valves are used, one at either end of the locomotive, and therefore, may be seventy or more feet apart. If one distributing valve is used there is introduced a large volume of pipe, hence the rate of application and of release will be slower than normal, unless other apparatus is added to the standard steam equipment. In addition, if the electric locomotives is arranged for double heading it generally is desirable to have under the control of the engineer on the leading locomotive, the independent brakes on the second locomotive. The latest type of brake for the electric locomotive, is known as the Type EL, and incorporates the features mentioned.

While the manipulation of this brake is the same as for the equipment used on the modern steam locomotive, the apparatus itself is different, because of factors, peculiar to the long and heavy locomotive units, with the extra volume of piping, the larger number of brake cylinders, etc.

As previously mentioned, the steam locomotive may have

the distributing valve located in close proximity to the engineman's valves, and the volumes are small. Some electric locomotives however, have two cabs and it is necessary to use two distributing valves, one for each cab. It may also be advantageous to even use two distributing valves on an exceedingly long one-cab locomotive. Normal conditions of operation are obtained by adding two valves, called transfer valves, to offset the effect of long operating pipes, and to make certain that the desired rate will be obtained for independent brake operations.

The Transfer Valve.—This transfer valve acts like a relay; it relays the braking functions to the second distributing valve, and if two locomotives are coupled together for double-heading, to the distributing valves on the second locomotive. One transfer valve is so interposed in the independent application and release pipes that the distributing valve is connected to the brake valves at the operating end only, and cut off from the brake valve at the non-operating end. The other transfer valve is so interposed in the independent-application and brake-cylinder pipes that the braking functions are relayed from the first distributing valve on the first locomotive to the others, and thus control of the independent brakes on the second locomotive, so desirable when double-heading, is secured.

The Three-Position Double Cut-Out Cock.—Where there is more than one brake valve on a locomotive, a cut-out cock is necessary under each, to cut-out the brake pipe at the brake valve on the non-operating end. All double-end electric locomotives have a two-position cut-out cock, the positions being brake pipe open, and brake pipe closed; but on locomotives which use transfer valves, a third position is necessary, and the device is called a three-position double cut-out cock. Three different positions of the handle correspond to the various functions of the valve. With the handle across the pipe, the brake pipe is open, and the transfer valve connection is open to the atmosphere, the main reservoir connection being blanked. This is the position in which the handle of the cock on the operating end should be.

The second position is when the handle is upward in line with the pipe. The brake pipe is then closed and the transfer

valve connection is open to the main reservoir This is the position on the non-operating end and on both ends of the second locomotive when double-heading. With this position the engineman at the front or operating end has complete control of the air on both locomotives.

To place the handle in the 3rd position requires that a stop pin be raised to go from the second to the third. In this position the brake pipe and main reservoir are closed and the transfer valve is open to the atmosphere. This is the position used when the locomotive is handled dead in a train.

Regenerative Interlock Valve.—Regenerative electric braking for negotiating mountain grades has become a standard on electric locomotives. While locomotives are regenerating, it often becomes necessary to use the air brakes, and unless some precaution is taken to prevent it the effect of an air brake application in addition to that of full regenerating, can cause the drivers to slip. The function of the regenerative interlock valve is to prevent automatically, the use of air and regenerative brakes at the same time. The interlock valve is placed in the brake cylinder pipe which comes from the distributing valve, and it also has a connection to the main cylinder.

An emergency application of the brakes predominates over regeneration and when made, regeneration is cut-out so that all the braking is done with the air brake. The service application, however, depends on regeneration. For instance, if the locomotive is regenerating then a service application cannot be made, and if a service application has been made and the locomotive is thrown into regeneration then the air brakes are released automatically. With the release of regenerative control, the air brakes will be re-applied automatically and to the same degree of holding power that preceded the regeneration, unless, in the meantime, the service application has been released manually.

An important advantage derived from this air brake arrangement combined with the power control equipment for the motors of the electric locomotive, is the ability to double-head, requiring only one engineman at the head-end of the train. The arrangement is such that the operator has the same degree of control of the second locomotive as the first

one, from which he is operating, and the locomotive brakes can be applied and released independently, the same as if only one locomotive were being used.

The Air Compressor.—On the electric locomotive, the method of maintaining the main air reservoir pressure, is different from that which is used on steam locomotives.

In the case of the latter, the pump operates automatically on a very slight reduction of air reservoir pressure, so that the main reservoir is kept at practically a constant pressure.

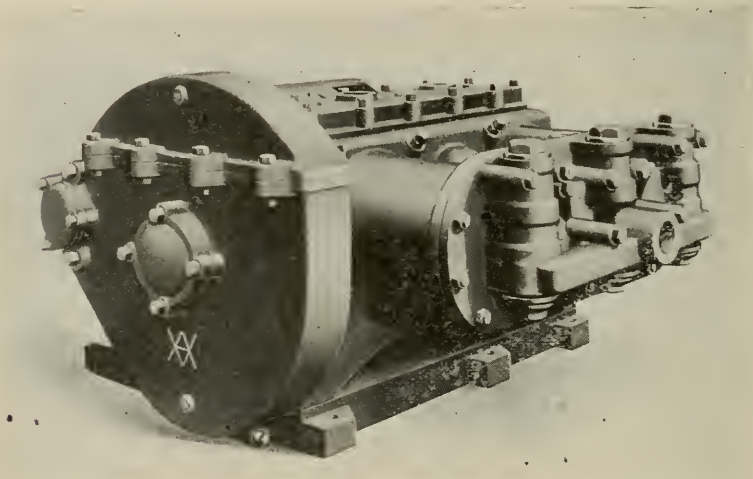


Fig. 58—Three-Cylinder, Two-Stage, Motor-Driven Air Compressor.

On the electric locomotive, however, the air compressor—Fig. 58—is driven by a motor which runs at a constant speed, and the capacity of the compressor is such that by operating about one-third of the time enough air is obtained for the requirements. It is not economical to run the motor at low speed, so that instead of maintaining constant pressure in the main reservoir it is usually allowed to vary over a range of 15 lb. For instance, with a pressure of 110 lb. in the train line, the pressure at which the compressor stops is about 140 lb., and this pressure must fall to about 125 lb. before the compressor is again cut-in. The compressor is controlled by means of an electric governor which can be set for any maximum and minimum pressures, and operates a switch for open-

ing and closing the electric circuit to the motor coupled to the compressor.

Air compressors for electric locomotives may be placed either in the cab or under the hood, depending upon the construction of the locomotive, or they may be located in a cradle underneath the floor. In any case they should be placed in such a position that ready access may be had to the commutators, brush holders, and oil cups. Suction strainers are connected by piping to the air inlet of their respective compressors, and should be so located as to insure a supply of clean, dry, cool air, as this provision adds materially to the efficiency and life of the compressor. Usually the strainers are located either in the cab, or on the roof, or under the hood. When the air compressor is operating, air is drawn into the cylinders through the suction strainer and past the inlet valves, compressed, and forced out past the discharge valves, and through radiating pipe to the main reservoirs. For electric locomotives double air-compressor units are desirable, especially in heavy service, to provide an ample supply of compressed air for braking and other purposes. They should be so arranged that they can be operated independently when necessary. If only one compressor is used, two main reservoirs are installed, but with a double compressor unit four main reservoirs are used for the purpose of storing an abundant supply of compressed air, which will permit of promptly releasing the brakes and recharging the system. These reservoirs also assist in cooling the compressed air and depositing moisture, oil or other foreign matter, allowing only clean, dry air to pass on to the brake system. The piping should be so installed as to drain into the reservoirs, and drain cocks applied in order to permit of easily draining the reservoirs. The reservoirs should be drained at regular intervals as an accumulation of water or other foreign matter is not only injurious but is also liable to seriously reduce the capacity.

The amount of radiating pipe necessary has to be decided according to the needs of each locality; where freezing temperatures are not encountered it may be omitted altogether. For obvious reasons the reservoirs and radiating pipe should be located at a safe distance from sources of heat, such as resistance grids, motors, etc. For the purpose of shutting off

the source of air supply when desired, a cut-out cock is placed in the main reservoir pipe, beyond the governor connection.

Mechanical Construction.—The mechanical constructions of a compressor and its driving motor are shown in the sectional views, Figs. 59 and 60. The motor armature shaft carries a pinion which meshes with a gear fitted to the crank shaft, the gear and pinion being enclosed in a gear case. In this design the center line of the cylinders is located slightly above that of the crank shaft in order to reduce the vertical component of the thrust and the consequent wear during the compression

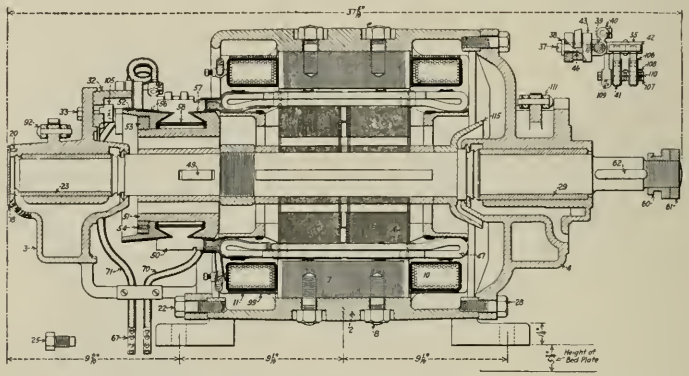


Fig. 59—Assembly of Motor for Driving the Two-Stage Compressor Shown in Fig. 58.

stroke. For that reason, the crank shafts of motors of this design should always rotate in a clockwise direction when viewed from the gear end. The compressor portion has two low-pressure cylinders, and one high-pressure, the latter being located between the other two. The low pressure cylinders receive air from the atmosphere through the suction inlet compress it to the first stage, and discharge it into an intercooler. From there it passes into the high pressure cylinder where the pressure is raised to the final amount. The air is then discharged into the reservoir.

The intercooler should consist of the equivalent of 100 feet of 2-in. pipe, arranged for rapid radiation of heat. This device serves to increase volumetric efficiency and enables the compressor to operate longer without overheating.

Lubrication.—The lubrication of the compressor is entirely automatic and requires no attention other than to replenish

the oil supply. The crank shaft bearings, connecting rods, and pistons are lubricated by the splash system, using oil which is contained in the crank case. As the crank shaft

NAMES OF PARTS OF MOTOR-COMPRESSOR SHOWN IN FIG. 59

Ref. No.		Ref. No.	
2	Field Yoke.	47	Armature Coil.
3	Front Bearing Housing.	49	Key for Commutator.
4	Rear Bearing Housing.	50	Commutator.
6	Armature.	51	Commutator Bushing.
7	Pole Piece.	52	Commutator Taper Ring.
8	Pole Piece Stud and Nut.	53	Commutator Nut.
10	Field Coil.	54	Commutator Set Screw.
11	Field Coil Brass Washer.	56	Outer Insulating V Ring for Commutator.
18	End Cover for Front Bearing Housing.	57	Inner Insulating V Ring for Commutator.
20	Screw for End Cover	58	Commutator Insulating Sleeve
22	Cap Screw for Front Bearing Housing.	60	Nut for removing Pinion.
23	Front Bearing.	61	Motor Shaft Jam Nut.
25	Screw for Bearing.	62	Key for Pinion.
28	Cap Screw for Rear Bearing Housing.	67	Connector for Leads.
29	Rear Bearing.	70	Field Lead.
32	Rocker Arm.	71	Commutator Lead.
33	Cap Screw for securing Rocker Arm.	92	Cotter Pin.
35	Carbon Holder.	99	Field Coil Washer.
37	Carbon Holder Cap Screw.	105	Nut for Rocker Arm.
38	Double Washer.	106	Lever for Carbon Holder.
39	Carbon Holder Double Nut.	108	Screw for securing Springs in Carbon Holder Spring Stud.
40	Carbon Holder Lead Screw.	109	Screw for clamping Spring Stud.
41	Carbon Holder Spring.	110	3/8" Brass Washer for Carbon Holder Spring Stud.
42	Carbon.	111	Top Cover for Bearings.
43	Insulating Washer.	115	Oil Guard for Armature
46	Rocker Arm Insulating Tube.		

rotates, oil is splashed into the cylinders and into the crank shaft bearings. Some of the oil seeps through the rear crank shaft bearings and enters the gear case, where it serves to lubricate the gear teeth. Part of this oil is carried up by the gear to the pinion and thence into the rear bearing oil well of the motor. It cannot, however, flood the motor, for there is a direct connection whereby any overflow returns to the latter through a cored passage between the oil well and the crank case. The motor bearings each have an oil well and are supplied with constant lubrication by means of the oil rings.

Electric Compressor Governor.—The governor is a device for automatically controlling the operation of the air compressor so that the air pressures will be held between pre-

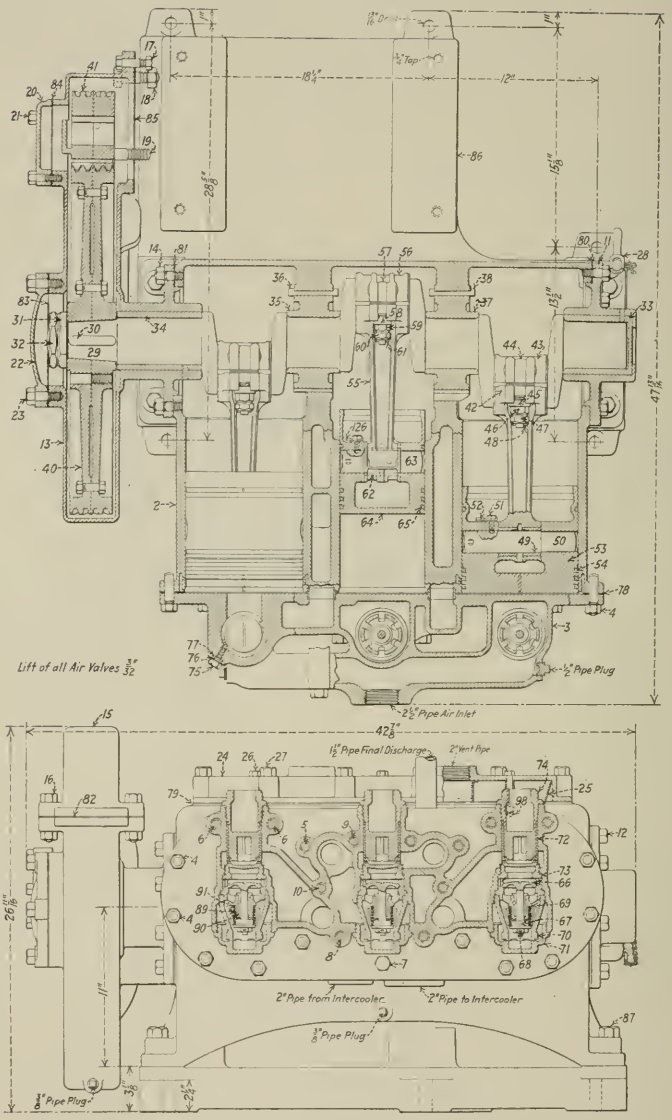

Lift of all Air Valves 3/32"
1/2" Pipe Plug
2 1/2" Pipe Air Inlet
1 1/2" Pipe Final Discharge
2" Vent Pipe
2" Pipe from Intercooler
2" Pipe to Intercooler
3/8" Pipe Plug
1/8" Pipe Plug

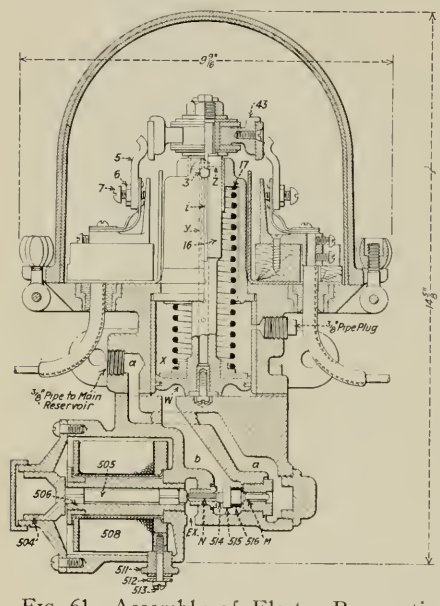
FIG. 60—Assembly of Three-Cylinder, Two-Stage, Air Compressor.

NAMES OF PARTS OF AIR-COMPRESSOR SHOWN IN FIG. 60

2 Cylinder and Crank Case.
3 Cylinder Cover.
4 Cylinder Cover Bolt and Nut.
5 Cylinder Cover Bolt and Nut.
6 Cylinder Cover Bolt and Nut.
7 Cylinder Cover Cap Screw.
8 Cylinder Cover Cap Screw.
9 Cylinder Cover Cap Screw.
10 Cylinder Cover Cap Screw.
11 Front Crank Case Cover.
12 Front Crank Case Cover Cap Screw.
13 Gear Case.
14 Gear Case Stud and Nut.
15 Gear Case Top Cover.
16 Gear Case Cover Bolt and Nut.
17 Dowel Bolt for Gear Case Pad.
18 Bolt and Nut for Gear Case and Motor Flange.
19 Cap Screw for Gear Case and Motor Flange.
20 Small Cap for Gear Case.
21 Cap Screw for Small Cap for Gear Case.
22 Center Cap for Gear Case.
23 Cap Screw for Center Cap for Gear Case.
24 Crank Case Top Cover.
25 Oil Separator.
27 5/8" x 2 1/2" Hex. Hd. Cap Screw for Crank Case Top Cover.
28 Crank Case Oil Fitting.
29 Crank Shaft.
30 Crank Shaft Key.
31 Crank Shaft Nut.
32 Crank Shaft Jam Nut.
33 Shaft Bearing Bush, Front End
34 Shaft Bearing Bush, Rear End
35 Shaft Bearing, Rear End.
36 Shaft Bearing Key, Rear End.
37 Shaft Bearing, Front End.
38 Shaft Bearing Key, Front End.
40 Gear.
41 Pinion.
42 Low Pressure Connecting Rod.
43 Low Pressure Connecting Rod Cap.
44 Low Pressure Connecting Rod Eye Bolt.
45 Washer for Low Pressure Connecting Rod Eye Bolt.
46 Nut for Low Pressure Connecting Rod Eye Bolt.
47 Jam Nut for Low Pressure Connecting Rod Eye Bolt.
48 Cotter for Low Pressure Connecting Rod Eye Bolt.
49 Low Pressure Connecting Rod Bush.
50 Wrist Pin with Dowel, for Low Pressure Piston.
51 Wrist Pin Set Screw.
52 Wrist Pin Set Screw Lock.
53 Low Pressure Piston.
54 Low Pressure Piston Ring.
55 High Pressure Connecting Rod
56 High Pressure Connecting Rod Cap.
57 High Pressure Connecting Rod Eye Bolt.
58 Washer for High Pressure Connecting Rod Eye Bolt.
59 Nut for High Pressure Connecting Rod Eye Bolt.
60 Jam Nut for High Pressure Connecting Rod Eye Bolt.
61 Cotter for High Pressure Connecting Rod Eye Bolt.
62 High Pressure Connecting Rod Bush.
63 Wrist Pin with Dowel, for High Pressure Piston.
64 High Pressure Piston.
65 High Pressure Piston Ring.
66 Inlet Valve.
67 Inlet Valve Nut.
69 Inlet Valve Seat.
70 Inlet Valve Cage.
71 Inlet Valve Cap Nut.
72 Discharge Valve.
73 Discharge Valve Seat.
74 Discharge Valve Chamber Cap.
76 3/8" Wrot Iron Washer.
77 3/8" Copper Gasket.
78 Cylinder Cover Gasket.
79 Crank Case Top Cover Gasket.
80 Front Crank Case Cover Gasket.
81 Gear Case and Crank Case Gasket.
82 Gear Case Top Cover Gasket.
83 Gear Case Center Cap Gasket.
84 Gear Case Small Cap Gasket.
85 Motor Gasket.
86 Bed Plate.
87 Cap Screw for securing Compressor to Bed Plate.
126 Wrist Pin Set Screw Lock.

determined minimum and maximum limits. The electric circuit to the motor is automatically made and broken as the air pressure falls below or rises above the limits for which the governor is set.

Where locomotives are being operated double-head, or a completed locomotive consists of two units, or where trains of cars are used, some means must be provided to insure that



3 Guide Pin.
5 Finger.
6 Adjusting Screw Jam Nut.
7 Finger Adjusting Screw.
16 Switch Piston and Rod, complete.
17 Piston Spring for Pressures above 40 lb.
43 Switch Spider.
504 Armature.
505 Armature Stem.
506 Magnet Core.
508 Magnet Coil.
510 Button Head Cap Screw.
511 Insulator.
512 Brass Washer.
513 Contact Screw.
514 Exhaust Valve.
515 Supply Valve.
516 Supply Valve Spring.

Fig. 61—Assembly of Electro-Pneumatic Compressor Switch.

each compressor furnishes its proper share of the supply of compressed air. This precaution must be taken because of the fact that where two or more compressors deliver air to a common supply pipe, whichever compressor happens to start first might supply all the air required to recharge the entire system as the pressure would begin to rise instead of decreasing to the amount necessary for starting the others.

The complete regulating equipment includes an electro-pneumatic compressor switch which is supplied for each compressor, the admission of air to and exhaust from, the air cylinder being controlled by an electrically operated magnet valve. In addition to the compressor switch there is a master

governor. This piece of apparatus operates from the air pressure, but instead of connecting power directly to the compressor, it connects the control circuit containing the magnet valve of the compressor switches which cause these switches to close and thus start the compressors. A compressor switch is shown in Figs. 61 and 62, and a master governor, as used for locomotive operation, is shown in Figs. 63 and 64.

Operation of the System.—The magnets of the compressor switches are connected in parallel between the negative wire

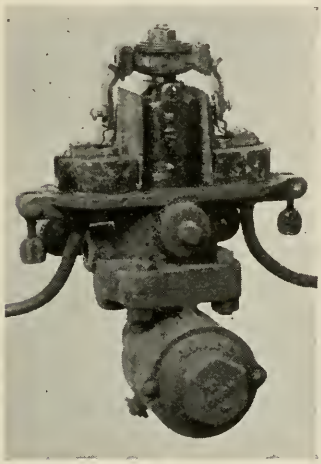


Fig. 62—Electro-Pneumatic Compressor Switch.

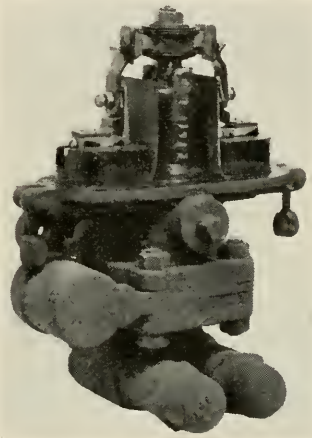


Fig. 63—Electrically Operated Compressor Governor.

of the battery circuit and a wire called the synchronizing wire, which extends throughout the train. The wiring of the system is so arranged that the opening and closing of any master governor in the train opens or closes the circuit controlling all the compressor switch magnets.

All the main reservoirs in the train are connected to a main reservoir pipe line, and on each car the main reservoir is connected to the pneumatic regulating portion of the master governor on that car. When the pressure in the main reservoir line falls below the cutting-in point of any one of the master governors, the switch of that governor is immediately closed, which in turn closes the circuit controlling the compressor switch magnets and causes all the compressors in the train to

start simultaneously. Whether one or more of the master governors cut-in at the same time is immaterial, since the compressors will continue to operate and raise the pressure in the main reservoir on each unit and in the main reservoir line throughout the train until such time as the governor set for the highest cutting-out pressure—this one will be the

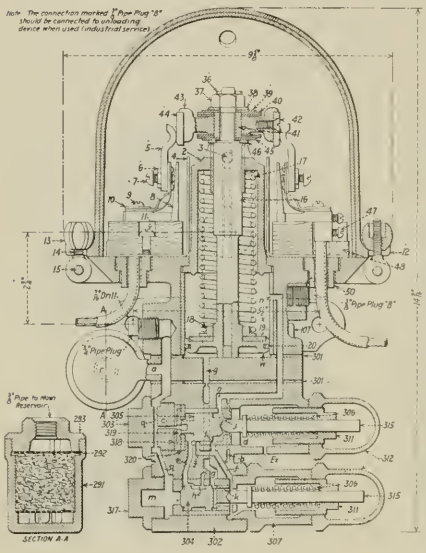

Note—The connection marked "Pipe Plug "B" should be connected to unloading device when used (industrial service)
SECTION A-A

FIG. 64—Assembly of Electrically Operated Compressor Governor.

2 Frame.
4 Finger.
11 Finger Board Screw.
12 Switch Cover.
16 Switch Piston and Rod.
17 Piston Spring.
18 Piston Spring Seat.
19 Piston Seal.
38 Piston Rod Brass Washer.
39 Piston Rod Fibre Washer.
40 Piston Rod Fibre Washer.
41 Square Fibre Brush.
43 Switch Spider.
44 Switch Spider Contact.
45 Piston Rod Fibre Washer.
46 Piston Rod Brass Washer.
47 Lead Screw.
50 Porcelain Bush for Leads.
301 Gasket.
302 Valve Case.
303 Cut-in Valve Cap.
304 Cut-out Valve.
305 Cut-in Valve.
311 Regulating Nut.
315 Spring Stem.
317 Cut-out Valve Cap.
318 Cut-in Valve Seat Retainer.
319 Cut-in Valve Leather Washer.
320 Cut-in Valve Washer.

governor that operates to cut-in the compressors—acts to open the circuit of the compressor switch magnets, and stop the operation of all compressors simultaneously.

Through the operation of this system, all compressors start and stop simultaneously, so that no one compressor is required to do more than its own share of work. This uniformity of compressor labor is not affected by excessive leakage on any unit, incorrect adjustment of governor or feed valve, relative efficiency of the compressor, or by other causes.

CHAPTER XVII

ELECTRIC LOCOMOTIVE DESIGN

In the preceding chapters some of the advantages of electrification and the benefits derived from electric operation were pointd out, and a comparison made of steam and electric locomotives as regards tractive effort and horsepower. Electric locomotive design will now be taken up and the construction and design of the various parts which go to make up the complete unit will be discussed.

Electrical Systems.—The electrical design of the locomotive will depend chiefly on the system of electrification with which it is to be used. The electrical systems may be classified under two headings, as follows:

1. Direct-current systems, which may be at either high or low voltage, varying from 600-700 volts up to 3,000 volts.

2. Alternating-current systems, which may be either single-phase or three-phase, with voltages from 3,300 volts up to 11,000 volts, or even higher.

The methods employed in collection of the electric power for operating the locomotive are important and interesting. Electricity for transportation was first used on the street railways; an overhead trolley, carrying 500 volts direct current, was used. As greater loads were demanded, due to the operation of more and larger cars, it was necessary to provide greater capacity in the trolley wire for carrying the required current. As the capacity of the wire was limited copper feeders were installed in parallel with the wire. When steam railroads operating heavy train service were electrified, using direct-current at 600-700 volts, a power greater than could ever be delivered by the single wire was required, so that the

third-rail contact system was used to provide the necessary current-carrying capacity.

In a typical third-rail contact system, the power is generated at a central power house and transmitted to substations as high-voltage three-phase alternating current. At the substations this three-phase power is reduced by transformers and changed by rotary converters into direct current. This direct current is distributed from the substation to the third rail by feeders. Ordinarily the track rails are used for conducting the return current, but in the case of heavy systems, copper cables, known as negative feeders, are connected in parallel with the rails so as to reduce the voltage-drop back to the substation.

There are limitations to the third-rail system. While in very dry climates 1200 volts can be used on the third rail, it may be said in general that this system of electrification is one limited to 700 volts. The comparatively low voltage, where heavy train service exists requiring considerable horsepower, means an abundance of copper, substations, etc., to care for the heavy current necessary for the operation of numerous heavy trains over long distances. To eliminate the excessive use of copper and substations a higher voltage was required. Subsequently the overhead contact system, using high-voltage single-phase or three-phase alternating current, was employed and high-voltage direct-current has been successfully used on the overhead system.

In typical single-phase systems, the power is transmitted at high voltage to the transformer substations, where it is transformed down to the workable voltage desired for the service and is connected directly to the overhead contact system as single-phase current.

In the case of the three-phase system, three-phase power instead of single-phase is delivered to the locomotives. This requires that two contact wires, insulated from each other, be placed above the track, the rails of the track acting as a third wire.

The high-voltage direct-current overhead system is similar to the low-voltage direct-current third-rail system. The power is transmitted in the same way, converted by rotating

machinery, but is fed at high voltage to an overhead conductor instead of to a third rail.

Electric Locomotive Classification.—Besides the fact that the internal apparatus of the electric locomotive must be designed according to the system over which it is to operate, there is another fundamental point of difference in the method employed in the collection of the current. From this point of view, the locomotives can be classified under two headings:

1. Those equipped with pantagraph contacts to collect the curent at high voltages from overhead wires located above and directly over the track.

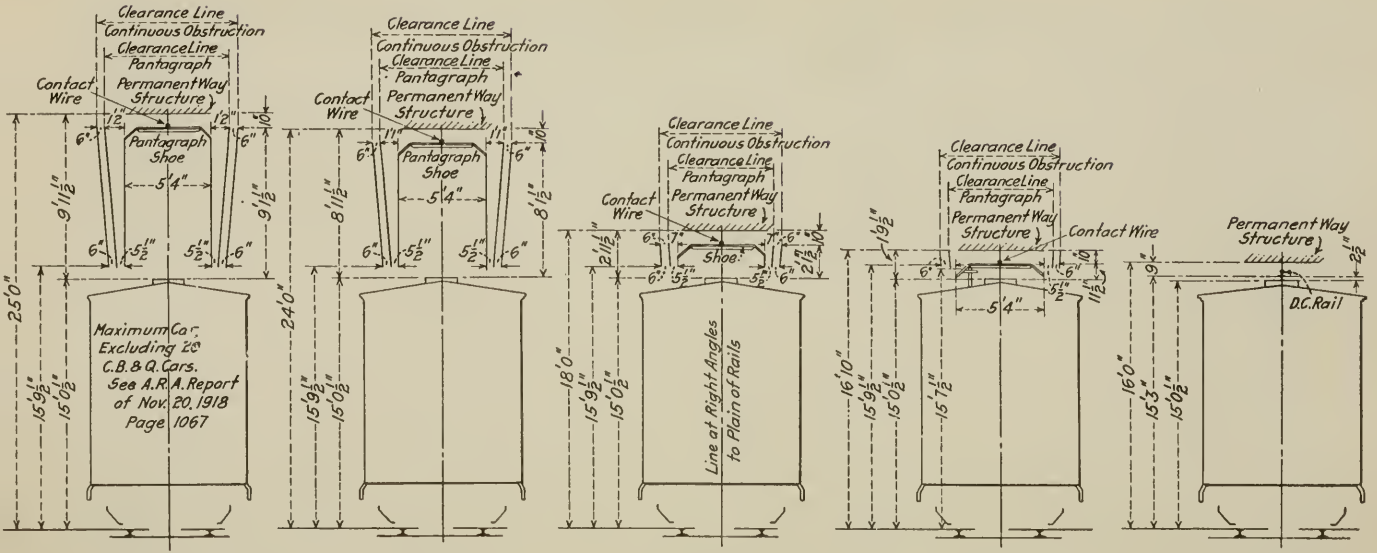
2. Those equipped with a third-rail contact shoes to collect the current from conductors located alongside of and adjacent to the running rails.

Before describing the design and construction of the overhead and the third-rail current collecting devices, it seems advisable to consider the construction and location of the electric conductors—the overhead wires and the third-rail.

With either type of construction the conductor must be insulated to prevent leakage of the electric current, and so located that there will be minimum interference with existing structures, and with the rolling equipment; and that it will permit of safe and satisfactory operation.

Overhead Working Conductors.—The clearance for overhead working conductors, as recommended by the American Electric Railway Engineering Association, is shown in Fig. 65; these diagrams show minimum clearances for five different cases. They are made up from the data in Table IV taking into consideration the clearance necessary where trainmen are required to give signals by hand and by lantern. The height of the wire above the top of the running rails is thus determined. It is an advantage, from the standpoint of the pantagraph trolley construction, to keep the wire lower than 24 feet. Many times overhead bridges span the tracks so that Cases 3 and 4 show normal and special minimum clearance.

The clearance lines take into consideration the sway of the pantagraph and its variation from central position. For instance, the car springs may have a maximum difference in height of 1 in. There may be a difference of ½ in. in elevation of track rails. The pantagraph being constructed of tubing,



Clearance for Trainman Giving Lantern Signals

Clearance for Trainman Giving Hand Signals

Normal Minimum Clearance Without Trainman on Cars

Special Minimum Clearance for High Voltage Wires Without Trainmen on Cars

Minimum Clearance D. C. Overhead

FIG. 65—Diagram Showing A. E. R. E. A. Recommended Clearances for Overhead Working Conductors.

with all joints as free from friction as possible, will sway at high speeds. The amount of swaying will depend on the height of the wire. In arriving at the width of the pantagraph shoe —5 ft. 4 in.—and in locating the clearance line, this sway is assumed as 6 in. toward either side at 22 ft. above the top of the running rails. The diagrams in Cases 1 and 2 show that as the wire becomes lower the clearance line approaches the width

TABLE IV. DIMENSION DATA FOR FIG. 65

Dimension	Case 1		Case 2		Case 3		Case 4		Case 5	
	Clearance for trainman giving				Normal minimum clearance without trainman on cars		Special minimum clearance for high voltage wires without trainman on cars		Minimum clearance for 600-volt d-c overhead contact wires	
	Lantern signals		Hand signals							
	Ft.	In.	Ft.	In.	Ft.	In.	Ft.	In.	Ft.	In
Distance between wire or face of contact rail and structure	0	10	0	10	0	10	0	10	0	9
Desirable clearance between rolling stock and wire, or contact rail	—	—	—	—	2	1½	0	11½	0	2½
Reach of trainman	7	8	7	8	—	—	—	—	—	—
Lantern, height of	1	0	—	—	—	—	—	—	—	—
Clearance	0	5½	0	5½	—	—	—	—	—	—
Total clearance above car	9	11½	8	11½	2	11½	1	9½	0	11½
Height of Car	15	0½	15	0½	15	0½	15	0½	15	0½
Height of permanent way structure	25	0	24	0	18	0	16	10	16	0

of the shoe. If special designs are used, additional clearance may be necessary as these diagrams show minimum clearances. Case 5 covers location and clearances of the d.c. overhead conductor; in many yards it is impossible to locate the third rail with gaps of a reasonable length, and in such cases an overhead rail is put up, collection of current being made by a short iron pantagraph collector. In the case of the high-tension line the pantagraph collector must be so designed that it will adapt itself to the various heights of trolley wire shown in Cases 1 to 4, inclusive.

Third-Rail Conductors.—The third-rail system consists of a conductor placed alongside of the track at a fixed distance away from the running rail and slightly above it.

Two different types of third rail are in use, the over-running

or top-contact rail; and the under-running or under-contact rail. In either case the rail is supported by means of insulators at intervals of about ten feet. A guard or covering is provided to prevent accidental contact with the third-rail and also to eliminate trouble due to snow and sleet. Generally the third-rail is made of a low carbon steel—much lower than used in the track rails—and it therefore has a low resistance—in other words, it is of high conductivity. The rail sections are joined by fish plates, and to insure electrical continuity are bonded with copper.

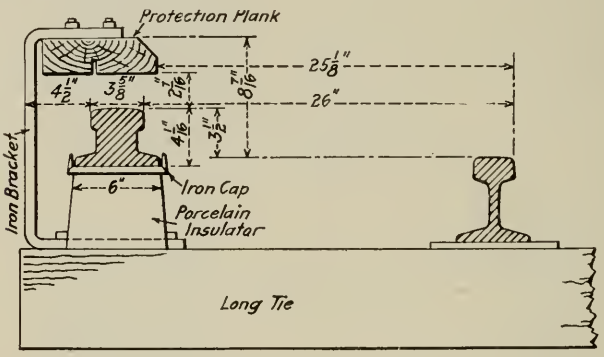


Fig. 66—Typical Over-Running Third Rail and Its Location with Reference to the Track.

The location of the typical over-runing third-rail in reference to the track is shown by Fig. 66. The insulators supporting this third-rail rest on long ties placed under the running rails and extending to one side at intervals of about ten feet. The type of insulator shown is a block of porcelain and sets over a short pin, which is screwed into the tie and keeps the insulator properly located. On top of the insulator is placed an iron cap to hold the rail. No clamping or fastening of the rail is necessary, as its own weight is sufficient to hold it in place and not permit it to turn over except in cases of derailment, when such a possibility is distinctly an advantage. In such an event little damage is done, and the rail can be replaced quickly.

The under-running third-rail layout is shown by Fig. 67. As

in the case of the over-running rail, it is supported at intervals of ten feet, on long ties. The method of support is not nearly as simple as the over-running rail. A curved bracket is required, and the rail is suspended from insulators, each consisting of two parts clamping around the rail for a length of approximately eight inches, and being held together by a clamp bolted to the bracket. As a means of protection, wooden strips are placed around the rail, except on the bottom surface. This construction is indicated in Fig. 67 as "section between brackets."

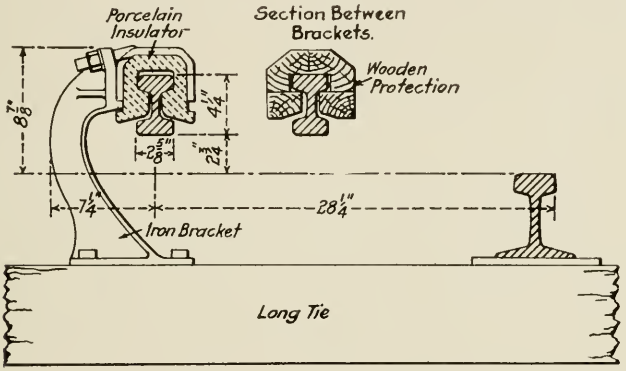


Fig. 67—A Common Type of Under-Running Third Rail.

From the foregoing description of the location of the electric conductors an idea can be formed as to the problem to be met in the collection of the electric power. In the case of heavy electric traction, large horsepower is developed per unit, which, in turn, means the collection of a large number of kilowatts from the conductor at almost any speed from starting to over 60 miles per hour. When taken from the third-rail the power is of low voltage and very high current, but can be collected easily by the third-rail shoes. In the case of the high-voltage alternating current system, the voltage is high and the current low, so that by providing proper clearance and insulation for the high voltage it is equally easy to collect the power. The current required with the high-voltage direct-current system, having a maximum voltage of 3000 volts in

this country, is considerable. While 3000 volts cut down the current demand, nevertheless considerable current must be handled and special provisions for its collection have been found necessary.

CHAPTER XVIII

THE PANTAGRAPH

As the overhead wire was successfully used with the single-phase high-voltage system prior to its use with the high-voltage direct-current system, the type of pantagraph designed for single-phase service will be considered in advance of the type for the high-voltage direct current; obviously, some difference in design would be expected between the two types. The high-voltage alternating-current collector is not required to handle comparatively large currents on account of the high voltage—often as high as 11,000 volts—even when large amounts of power are collected. While the high-voltage direct current of 3,000 volts is a high voltage for direct current, it is approximately only one-fourth of the alternating-current voltage, so that in the direct-current system, for the same amount of power, the current collected will be nearly four times that for the single-phase system. The collection of the current required for the large locomotive units has been a rather difficult problem, but that it has been solved, will be brought out further on.

General Design and Construction.—In the preceding chapter, clearance diagrams for overhead conductors, as recommended by the American Electric Railway Engineering Association, were given. These diagrams show heights ranging from 16 ft. 10 in. to 25 ft.; on a large system overhead wires may be anywhere between these limits. Generally the wire will be kept at a height of 22 ft. to 24 ft. but, due to overhead bridges or other causes, the wires will have to be lower than the standard height in order to pass obstructions.

The pantagraph then, must be so built that it will operate satisfactorily between these limits and must remain in continuous contact with the overhead wire. It must be as light

as strength will allow, so as to reduce inertia to a minimum and enable the shoe of the pantagraph to keep in contact with the wire at all times and at high speeds. It must be strongly built as it is subjected to considerable strain, particularly when mounted on a passenger locomotive running at 60 to 70 miles an hour. With the trolley wire at normal height, the shoe of the pantagraph is 8 to 10 feet above the roof of the locomotive and, as the swaying of the locomotive is transmitted to the pantagraph it must be strong enough to withstand this lateral strain which is at great leverage. It must also be strong enough to withstand the blows received at "special work" in the trolley wire, as at cross-overs, sidings, etc., and to withstand the sudden pressure due to the wire passing under bridges, etc. The grade or slope of the wire, when passing under bridges should not be too steep—preferably not more than 1 per cent; too great a slope will cause excessive pressure to be exerted on the shoe and frame of the pantagraph when operating at high speeds. To withstand such service the pantagraph would have to be strengthened, resulting in more weight, which is a disadvantage. Some idea of the blow exerted under such conditions can be formed when it is considered that at 60 miles per hour the speed is 88 feet per second and if the slope of the wire was 3 per cent the pantagraph would be pushed down nearly 3 feet in a second. To keep the shoe in proper contact, an upward pressure of approximately 12 lb. has been found to be best. Due to the friction of the various parts and bearings of the pantagraph, the pressure required to push it down will be approximately 17 lb. to 20 lb. This is the required pressure when pushed down slowly, but when pushed at the rate of 3 feet per second the inertia enters into consideration and the pressure will be very much higher.

In general appearance, all pantagraphs are alike as there is very little difference in construction except in details of shoe design and in methods employed to keep the pantagraph shoe against the wire. The same frame and practically the same raising and lowering sections or parts could be used on a high-speed passenger locomotive or a freight locomotive with single-phase 11,000-volt current supply; or in connection

with the collection of current from the high-voltage direct-current overhead wire at 3000 volts. It is, however, necessary to consider the shoe details in designs for the different types of locomotives and for the different electrical systems.

For high-speed service it is very important to have the shoe flexibily supported to the main framework of the pantagraph so that it will respond to the slight irregularities in the trolley wires and thereby eliminate sparking; constant contact is then maintained which would not exist without this feature. The shoe itself is of small mass compared to the whole pantagraph frame so that while the flexibly supported shoe will quickly adjust itself to the irregularities, the

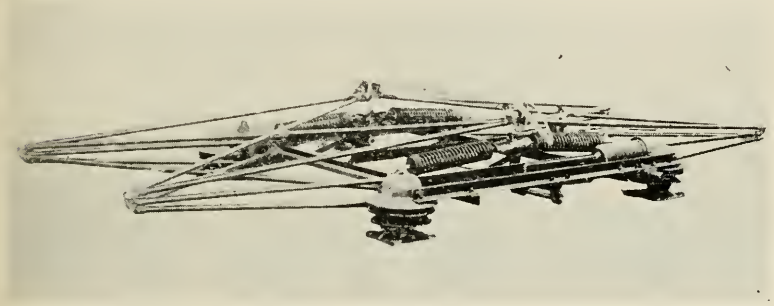


Fig. 68—Standard Pantagraph Frame Fitted with Flexible Shoe and Designed for Operating with 11,000 Volts at the Trolley.

frame, due to its inertia, will not respond; without this flexibility sparking would occur.

A standard pantagraph frame fitted with a flexible shoe for high-speed service and for the collection of the power at 11000 volts is shown in its "Down" or "Lock" position in Fig. 68 and also at nearly its maximum height or raised position in Fig. 69. The pantagraph is secured to a base made up of angle iron, mounted on insulators.

Pantagraph Insulators.—The insulators are mounted on steel pins having wide bases which are bolted to the roof of the locomotive. Some installations using 11000 volts have four insulators bolted to a frame which is also insulated from the roof of the locomotive, so that between the 11000 volts and ground there are two insulators in series, thus giving

double insulation. The detail design of this high-voltage insulator is shown in Fig. 70. An iron cap A, with an outside diameter greater than the porcelain petticoats forms the top part of the insulator. An insulator on top of a locomotive is

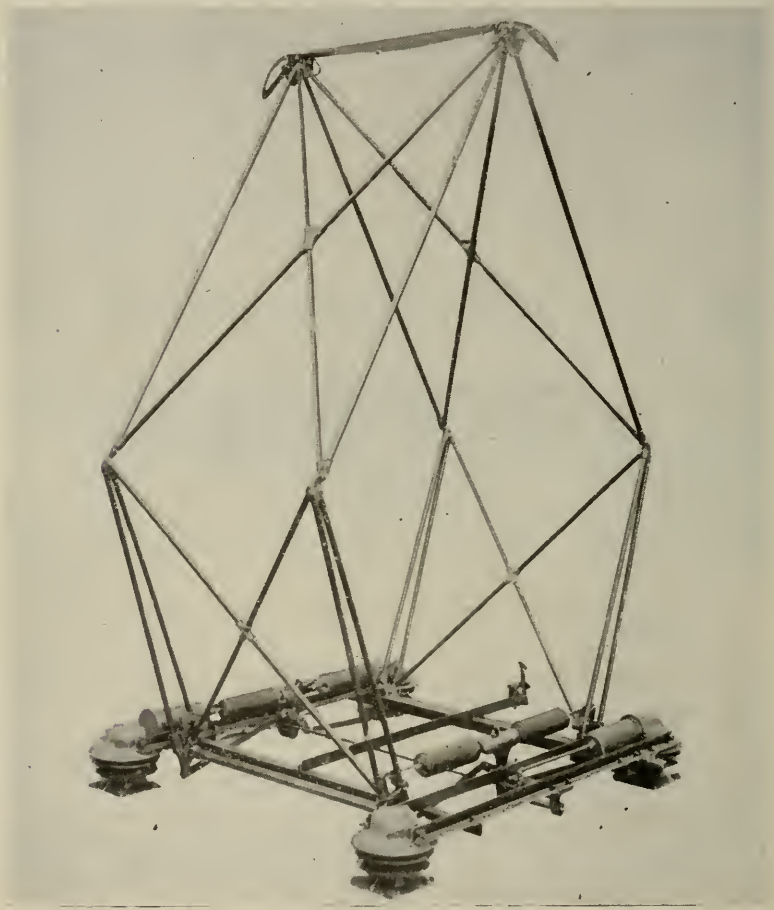


Fig. 69—Standard Pantagraph in Raised Position.

subjected to damage from external sources and one of the petticoat type especially, should be protected. As shown in the illustrations, the angle iron base of the pantagraph is bolted to the iron cap; some form of cap cemented to the insulator is necessary, and it is an easy matter to design one

with a flange to protect the porcelain. Between the steel cap and the first porcelain petticoat is placed a lead washer or disc B, 2⅞ in. in diameter, to form a cushion and to prevent breakages while assembling the parts. Also sufficient space is formed so that the rest of the space may be filled by cement C, and thus the steel cap does not come into contact with the porcelain. Between the second petticoat and the steel pin E, there is placed a steel disc D, 2⅛ in. in diameter. The pin is

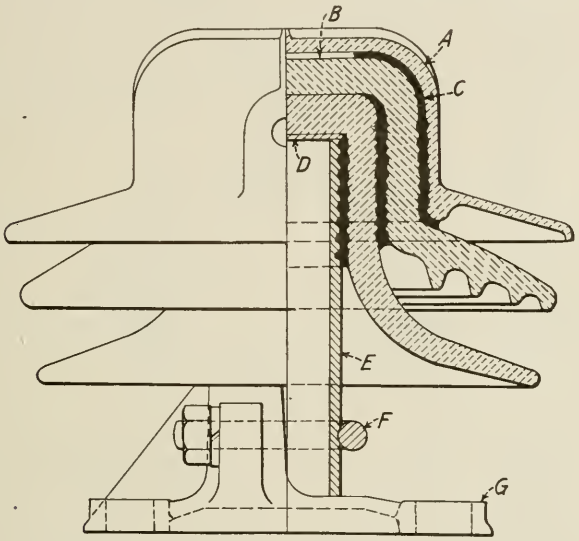


Fig. 70—High-Voltage Insulators Support the Pantagraph Frame.

fastened to the insulator base G, by the U-bolt F. This particular type of insulator is rugged and moreover electrically, has a very high factor of safety.

Another and less costly method of insulation designed for use with 3000-volt direct-current is illustrated in Fig. 75.

Pantagraph Framework.—A typical construction is shown in Fig. 71. The framework consists of four movable members, two upper and two lower. The two upper members are hinged together at the top and the upper end of each lower frame is clamped securely to a casting which is pinned to a cross shaft, of which there are two placed parallel to each other. The casting to which the frame is clamped also includes a cam over which passes a chain extending from the

spring. The curvature of the cam is such that the shoe will exert a fairly uniform pressure throughout the operating range of the pantagraph but will increase near the down or locked position, so that when the pantagraph latch is unlocked

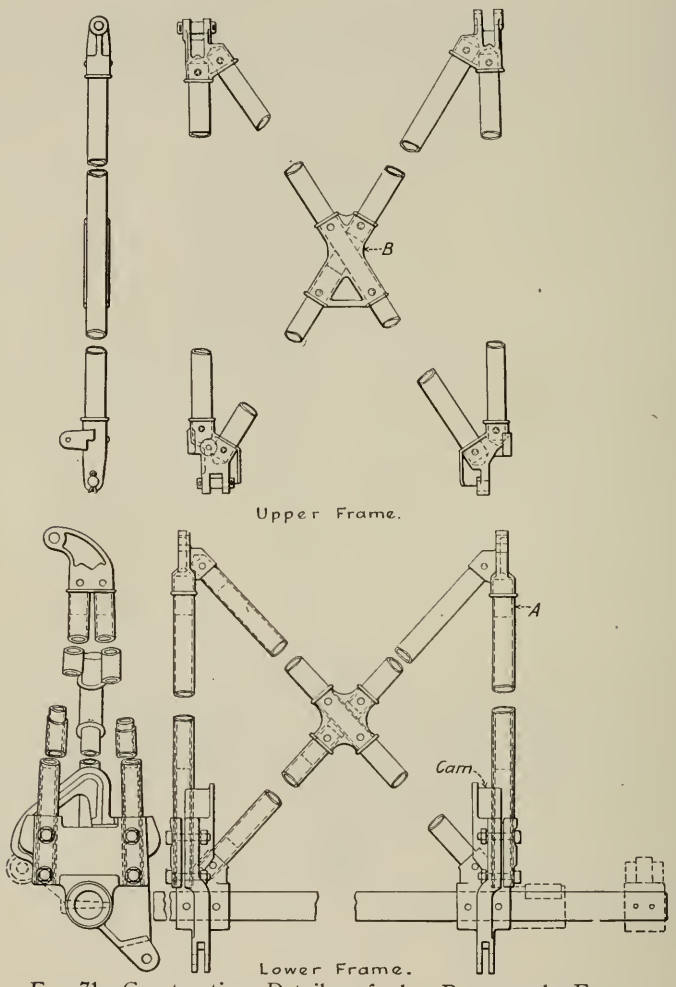


FIG. 71—Construction Details of the Pantagraph Frame.

or released, the trolley will start to rise promptly and quickly; when lowered, increase in pressure tends to cushion it.

Pantagraphs designed for use on equipment operated at high

speeds have tubes made from high carbon steel. The frames are cross-braced to give lateral stability. The side members are built up of two tubes, one inside of the other.

The first designs of pantagraph trolleys had horizontal cross members so that each frame section was rectangular in shape. With these horizontal cross members eliminated, more space is available on the roof of the locomotive without detriment to the strength and stability of the pantagraph.

The pantagraph trolley illustrated in Figs. 68 and 69 is the most common type; it is raised by means of springs, and lowered by air pressure. The springs consist of two sets of two each; they work under tension and exert a force which is

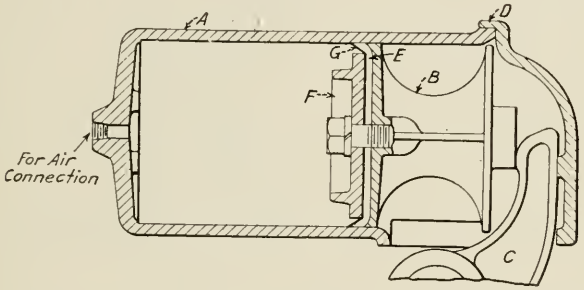


Fig. 72—Air-Cylinder for Lowering the Pantagraph.

transmitted from the springs, through the chains and cams, to the two shafts which rotate and thus raise the frame.

Air pressure is used to lowed the pantagraph, the reverse rotation of the shafts being accomplished by levers and links connected to two air pistons, one located on either side as shown in the illustration.

The details of the piston are shown in Fig. 72. The cast iron cylinder A, is tapped for air connection as shown. The end of the piston B, pushes against the lever C, the other end of which is connected to the links running to the levers on the shafts. The piston is limited in travel by the lever coming up against the cylinder cover D. A form of piston leather similar in design to the piston leathers of air operated multiple-unit control switches, is used; the piston B, is slightly cupped so as to fit the leathers which are cup shaped. The piston leather E, is 3-ply, each ply being separate but the three formed together. Between the leather and the cast iron

washer indicated as F, is placed the piston leather expander G.

The Latch.—When the pantagraph trolley is lowered, it is held in the "down" position by means of a latch which catches over the cross casting B, of the upper frame—Fig. 71. The latch is unlocked by air pressure, releasing the pantagraph which is carried up by the springs. The details of the complete latch are shown in Fig. 73. It consists of a cylinder A, latch B, piston rod C, retaining plate D, piston leather E—of

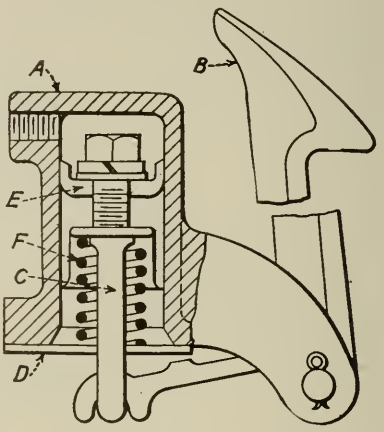


Fig. 73—Details of Latch.

same general construction, with follower and expander, as in the air cylinder; and spring F.

Pantagraph Shoe for Alternating Current.—The general design of the pantagraph shoe depends largely on the class of service in which the locomotive is to operate. If the pantagraph is mounted on a high-speed passenger locomotive or multiple-unit car, comparatively small currents are required. Where this current does not exceed 100 amperes at starting and is approximately 50 amperes at full speed, the shoe can be made of sheet steel 4 in. wide and ½ in thick. In high-speed service, the shoe should be flexibly supported; this is accomplished by inserting between the shoe and the frame a small pantagraph only 4 in. to 5 in. high at either end, fitted with light springs which are under compression when the shoe is against the wire. This arrangement gives the shoe a vertical movement of approximately 2 in. to 3 in. independent of the movement of the pantagraph frame itself. The weight of the shoe is extremely light compared with the weight of

the frame and therefore, due to the slight inertia, it will readily accommodate itself to irregularities of the wire, whereas the frame could not respond so quickly. Not only do these small pantagraphs, have a vertical movement, but they also allow the shoe to drag slightly in either direction. This design secures quicker movement of the shoe and it thus follows, more nearly, the variations in the wire.

On either end of the wearing section of the pantagraph shoe is mounted a horn—for lightness it is made of aluminum; the curvature of the horn is such that when entering from a cross-over, and picking up the trolley wire, a blow will not result, but the wire will pass smoothly over the horn to contact with the steel wearing section. A copper shunt at each end by-passes the current around the flexible connections of the shoe. One end of the shunt is connected to the horn casting, to which the wearing plate is attached, and the other end to the frame. A hook is provided at the end of the horn so that if, due to slight displacement of the wire or from other causes, the overhead contact wire should slip off the steel wearing section to the aluminum horn, the hook would normally prevent it from slipping entirely off the shoe and thus will prevent damage to the pantagraph due to "hooking over" the wire. For slow-speed operation this flexible shoe arrangement is not generally required although it is desirable.

If the current exceeds 100 amperes in starting, more metal is required in the shoe to absorb the heat. To handle starting currents of 250 amperes and running currents of 150 amperes, the shoe must be six inches wide and not less than ⅛-inch thick. When the starting current exceeds 250 amperes, it is desirable to place copper strips on the steel shoe, and currents up to 500 amperes can then be collected satisfactorily.

Pantagraph Shoe for High-Voltage Direct Current.—The foregoing has described rather fully, the construction and design of the pantagraph trolley for high-voltage single-phase operation on locomotives of various speeds and capacity. While the pantagraph was being developed in connection with single-phase operation, the direct-current system had not been used at the high voltage of 2400 volts or 3000 volts, so that for heavy traction, the direct current was being collected from a third rail. In later years, however, the high-voltage

direct-current has been developed and as, on account of insulation and creepage distances this high voltage could not be handled on a third-rail, it has been necessary to use an overhead wire. It therefore became necessary to consider the pantagraph type of collector, as it is, in general, a high-speed collector. The problem involved, however, the questions of how to collect from the wire, the amount of current necessary; a form of type of shoe that would satisfactorily collect the high currents required.

The first type of shoe used in this service was of a roller design. It consisted of a steel tube 5 in. in diameter, 24 in. long, and of ⅛ in. thickness after being machined both inside and outside. A shoe of this type, fitted with two horns, was found to be extremely heavy for pantagraph trolley construction; the complete roller, including the bearings, weighed approximately 31 lb. as compared with 5 lb. for sliding type of shoe. In order that the roller would follow the irregularities of the trolley wire, some flexibility was secured by operating with a pressure of approximately 35 to 38 lb. against the wire. This high pressure was sufficient to raise the contact wire to a height at which the weight of the wire equalized the upward pressure of the pantagraph, and, as the hangers supporting the trolley wire from the messenger cable were of strap steel looped over the messenger, and permitted free upward movement of the wire, the flexibility was in the trolley wire rather than in the shoe. While the roller shoe was developed so that it would operate with some degree of success it was not an ideal arrangement. The ordinary type of bearings could not be used, as after a short period of service the roller would jam and cease to revolve and immediately a groove would be worn in the roller or a flot spot formed, rendering it unfit for service. While special oil-lubricated sleeve bearings gave fairly satisfactory service for freight service at speeds of 15 to 30 miles per hour, there was excessive wear in passenger service at speeds of 45 to 50 miles per hour and special roller bearings were necessary.

The operation of the roller type of pantagraph shoe was so unsatisfactory that a study was made as to what could be accomplished with the sliding shoe in high-voltage direct-current service. Not alone was this type of pantagraph

heavy and costly, but the principle of design did not lend itself to high-speed heavy traction as the rapid revolution of the roller at high speeds made it necessary to have the balance perfect.

As already mentioned, currents up to 500 amperes had been collected satisfactorily by a single shoe fitted with copper contacts. To collect the current demanded with 3000-volt direct-current operation, a double shoe has been developed

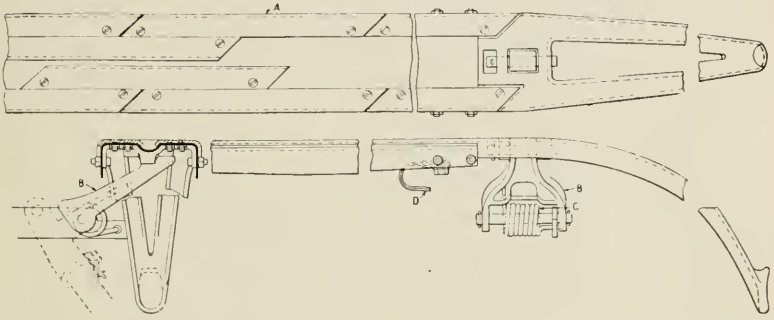


FIG. 74—Details of Pantagraph Shoe and Method of Mounting on Frame.

which is capable of collecting 1200 amperes at starting and 600 amperes at a speed of 60 to 70 miles per hour.

The pantagraph construction is the same as the single shoe type except that instead of having one shoe located centrally, there are two similar shoes placed parallel to each other 6 to 8 inches apart. Each shoe is flexibly supported and operates independently of the other. The details of the shoe, construction and the method of mounting on the frame are shown in Fig. 74.

The sliding shoe has screwed to it, strips of copper, A; at the center these strips are double thickness as the trolley wire is near the center of the shoe the greater part of the time and there is greater wear than occurs at the ends. For mounting the shoe, each horn is fitted with an arm or lever B, which is pinned to the frame. A spring C is used to obtain the auxiliary pressure and to provide flexibility. Shunts, D, of braided copper, carry the current around joints and springs.

Pantagraph Insulator for 3000-Volt Direct Current.—With 3000-volt operation, it is not necessary to fit the pantagraph

with the high-voltage insulator illustrated by Fig. 62, but a cheaper one can be used. For this service a type as shown by Fig. 75 has been developed.

The porcelain insulator A, is secured to the stand B, by the clamp C. Between the clamp and the porcelain is placed a

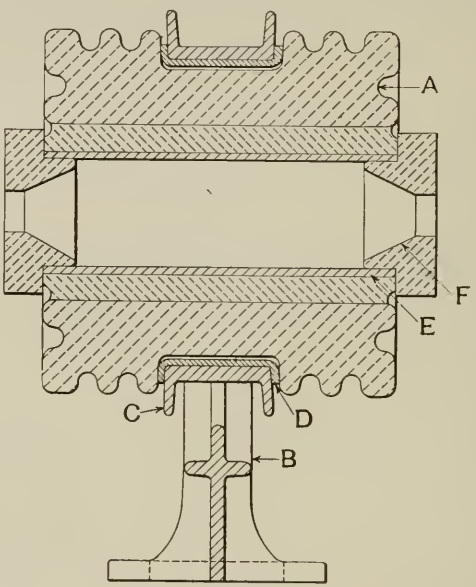


Fig. 75—A Pantagraph Supporting Insulator for 3000-Volt Operation.

lead D. A wrought iron bushing E, fits the inner bore and malleable iron bushings F, are provided for the mounting of the base of the pantagraph on the insulators.

Methods of Pantagraph Operation.—The pantagraphs described are of a type which can almost be termed "standard" in this country, in that they are spring-raised and air-lowered. There are however, several other methods of pantagraph operation used which will be described briefly.

One of the simplest is the "spring-raised hand-lowered." This arrangement was used in many of the earliest types; it follows the same principle as the trolley used with the ordinary street car. One or two tension springs is sufficient to obtain the required pressure and an insulated rope fastened

to the under part of the shoe or frame provides the means of pulling the trolley down by hand.

A type in which the method of operation is just the opposite of the American "Standard" has been used extensively in Europe. Air is used to raise the pantagraph and it is lowered by gravity. Pantagraphs of this type have been used in this country, although not extensively. Their great disadvantage is, that when there is no air on the locomotive the shoe must be held against the wire until the electric compressor has operated long enough to pump up an air pressure sufficient to keep the shoe in contact.

In the operation of the "standard" air-lowered pantagraph, the full air pressure should not be admitted to the "trolley down "cylinders, as the motion will be too rapid, resulting in breakage of the frame, etc. To prevent a sudden pressure, a diaphragm having a hole 1-16 in. in diameter should be inserted at a union in the air connection to the main cylinder; the pantagraph can then be brought down slowly. Rubber hose is used for the air connections and these must be of sufficient length so that under conditions of snow and sleet the creepage distance will be ample. Care must be taken that the rubber hose does not touch the roof, otherwise the creepage distance will be cut down and flashing of the high voltage to ground will occur.

The Oil Circuit Breaker.—The current collected by the pantagraph is carried into the cab through a high tension cable passing through a pipe. One end of this cable is secured to the framework of the pantagraph and sufficient length of cable is left outside of the pipe to prevent creepage of the current during rain or sleet—usually from 3 to 4 feet. The cable terminates in an oil circuit breaker. This circuit breaker is used to close the high-voltage current to the transformer and it corresponds to the main switch of a low-voltage circuit but, in addition, its action is automatic, opening on overloads or short circuits in the locomotive.

One of the latest type of circuit breaker is shown in Fig. 76. It consists of an operating handle, fitted with a releasing trigger which is connected to a rod of insulating material carrying contacts. When the handle is pushed down the movable con-

tacts are raised and make contact with stationary contacts, thereby connecting the high tension line to the transformer. The contacts are surrounded by oil carried in a tank; the oil is used to extinguish the high-voltage electric arc which is

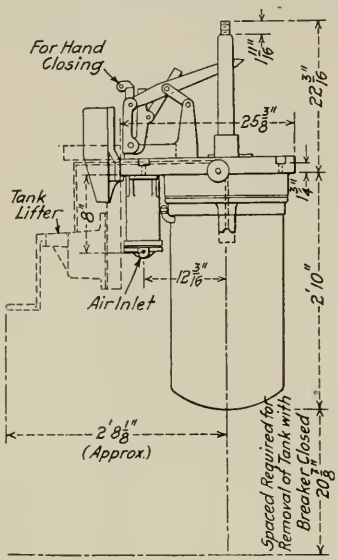


FIG. 76—Oil Circuit-Breaker for Locomotive Use.

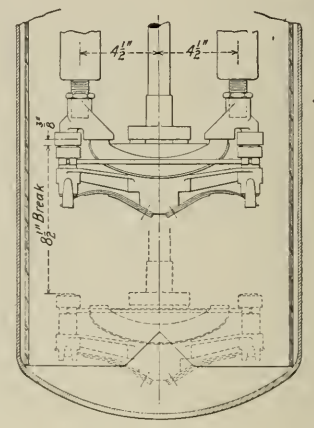


FIG. 77—Contact Arrangement of circuit-breaker.

formed as the circuit breaker opens, the effect of the arc being nearly negligible when broken in the oil.

In addition to the hand lever an air piston is provided and permits remote control of the breaker from either end of the cab. The use of the hand lever is necessary only when there is no air available on the locomotive as when first starting.

The contact arrangement in the circuit-breaker tank is shown in Fig. 77. The strips on the movable plunger which carry the greater part of the current after the switch is closed, are protected from being burned by the arc, when the switch is opened, by means of two auxiliary contacts which are under spring tension; these auxiliary contacts are first to close and last to open in the operation of the switch.

CHAPTER XIX

THE THIRD-RAIL SHOES

There are two types of third-rails, the over-running and the under-running. The location of the contact surfaces in respect to the running rails is nearly the same in the two types; in the case of the over-running type, the center of the contact surface is located approximately 27¾ in. from the gage line of the running rail and 3½ in. above the top of it, while in the case of the under-running third rail the contact is 28¼ in. from the gage line and 2½ in. above the top. Sectional views of the two types of construction, were shown in Chapter XVII.

In general the construction of the third-rail-shoe mechanism is the same for either type but there may sometimes be conditions which will affect the design somewhat. For instance, the New Haven passenger locomotives operate for a greater part of the time on alternating current, the current being collected from an overhead wire by means of a pantagraph but, as these same locomotives also operate over the tracks of the New York Central it is necessary also to use third-rail shoes and these must be designed so that they can be raised out of the way to avoid breaking off, when the locomotive is operating on the alternating-current system.

The Stationary Third-Rail Shoe.—Before going into the details of construction of the folding type of contact shoe, the stationary or fixed type will be described. This type of shoe mechanism is used on the Pennsylvania locomotives operating into the New York Terminal, and is shown in Figs. 78 and 79. Two hangers, H, are bolted to the truck frame. These hangers are provided to carry the shoe-beam, B, which is made of an insulating material—usually of wood. The insu-

lating material is necessary, due to the fact that when the shoes are in contact with the third rail all metal parts connected with them are "alive" and the voltage must be kept from any part of the locomotive that is grounded. Sufficient distance on the shoe-beam must be allowed between the hanger and the "live parts," so that creepage will not occur even when the beam is covered with dirt, moisture or snow. It is important, however, to keep the beam clean and properly painted with an insulating paint so as to increase the factor of

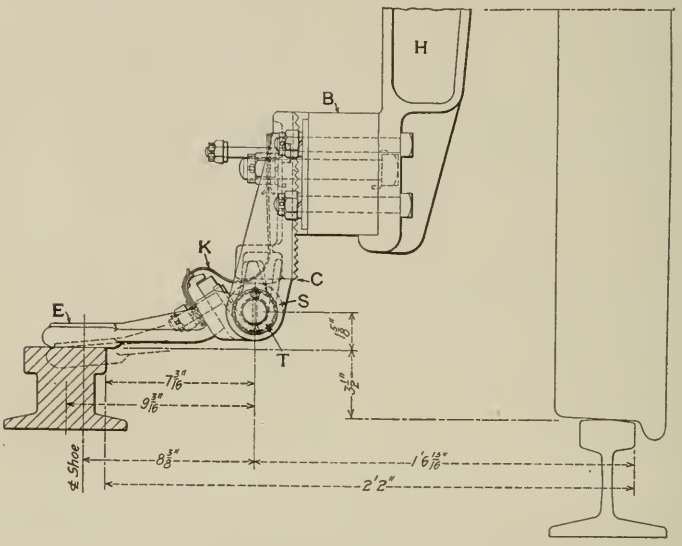


FIG. 78—One Type of Over-running Third Rail Shoe.

safety and to prevent any chance of this creepage. In this connection it might be well to explain the term "creepage." Voltage is analogous to pressure, and the distance which electric current will jump through the air varies with the voltage. The distance, however, is extremely short, being only a small fraction of an inch for 11,000 volts—about ¼ in. While the distance that an electric current of 600 volts will jump is very small, the creepage distance may be much greater and depends on the condition of the surface over which the current creeps. As an illustration of this, consider the third-rail beam: If this beam is charred and wet, and covered with dust

and dirt, the voltage may actually cause the current to "creep" several inches along the surface of the beam to "ground," thereby causing a short circuit. No creepage would exist if the beam was kept smooth, and painted and clean.

On the beam, B, is mounted the toothed bracket, C. This bracket is adjustable so that the shoes can be set by gauge to a certain height; the adjustment is made by loosening the bolts—D, Fig. 79—and slipping the shoes either up or down, one or more teeth, as is found necessary. The location of the

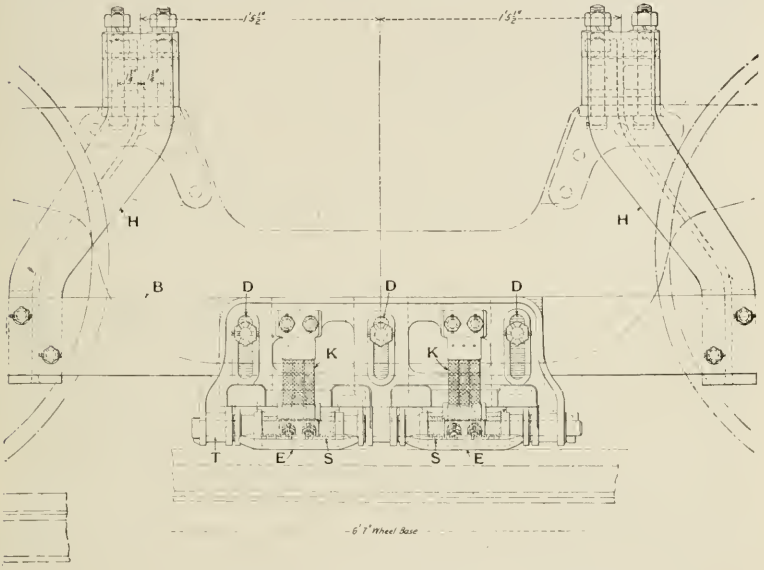


Fig. 79—Method of Supporting Third-Rail Shoes.

third-rail bears a fixed relation to the running rails or track so that a gauge for checking up the location of the shoes may be easily provided. A simple one can be made from a board, reinforced with iron where necessary to prevent wear. This gauge is set on the running rails and is provided with an extension which passes under the shoe. In Fig. 78 there is shown a dotted position of the shoe, E, which is 1 in. below the normal position——the lowest allowable position. The shoe must not be more than 1 in. below the horizontal or operating position, nor be less than ¾ in. when hanging free—

not resting on the rail. These dimensions give the permissible variation in location of the shoe, and any discrepancies can easily be detected by means of the gauge.

While the third-rail is carried on either insulators or brackets mounted on extended ties, and is located in reference to the running rails, there are irregularities in the third-rail which must be followed by the shoes. To aid in this, the springs S, are used; these springs are slipped over the shaft, T, around which the shoe swings. As shown in the illustration, the shoes are beveled or rounded on either side in order to eliminate any sharp corners which might catch on the third-rail, and result in breakage of the shoe. To avoid breakage, it also is essential that the shoes be kept to gauge, otherwise considerable trouble will be experienced from this source. To prevent any serious damage to the equipment the shoes are made weaker than the other parts of the apparatus, so that they will break easily if they should strike any object and thus avoid placing a severe strain upon the bracket and the shoe beam.

As in the case of the pantagraph trolley, braided copper shunts K carry the current around the joints and bearings. These shunts are very much larger, due to the fact that the current taken by the third-rail shoes is very much greater than that taken by the pantagraph shoe in the 11,000-volt operation. The high voltage is 18 to 20 times greater than the third-rail voltage, so that for the same horsepower it is necessary to collect from the third rail 18 to 20 times the amount of electric current. The lower end of the shunt is bolted directly to the shoe casting, and the other end is bolted to a part of the bracket which forms the terminal for the shoe lead or cable.

The under-running third-rail shoe is practically of the same construction, except that the pressure is in the opposite direction—upward—and that the normal position, when hanging free of the rail, must be higher than the third-rail contact surface in order to provide for sufficient upward pressure against the inverted rail.

The Folding Third-Rail Shoe.—A third-rail shoe of folding construction is used on the New York, New Haven and Hartford locomotives and multiple-unit cars, which are equipped

for overhead operation, but also operate over the third-rail system on the New York Central. As previously mentioned, the mechanism is arranged so that the shoe can be raised when not running on the third-rail system, so as to be within the clearance line on the New Haven road. In addition to this feature the shoe can be lowered away from the third-rail approximately 5 in. This is an "emergency" feature, and provides a means of disconnecting the electric power entirely from the locomotive in case of a short circuit which would not be disrupted by the blowing of the fuses. On a large electrified system such as the New York Central, where heavy drafts of power are taken by each locomotive, and where the current delivered to the third rail by any one of the many substations is several thousand amperes at 600 volts at the peaks, it is necessary to set the circuit breakers to "trip out," at a comparatively high setting—approximately 8,000 amperes. Under such conditions a situation could arise where the short-circuit arc would not require sufficient current to blow the breakers in the substations, so that this emergency feature is a desirable one. An interesting point in this connection is that, when the third-rail shoe leaves the rail, even with the heavy main motor current passing through the shoe, an electric arc does not persist, but is quickly disrupted, due to a magnetic blowout action.

The details of the shoe and operating mechanism are shown in Fig. 80. The assembly is mounted on a shoe beam N, which is supported from the truck. Adjustment for height is provided for by a series of teeth T, as in the other design of shoe. Due to the size of the mechanism, it is not as practicable, in this case, to adjust the casting on the beam as it is to adjust each end of the beam at its point of support; the latter arrangement is followed.

Remote control of the operation of the shoe from the inside of the locomotive is effected by air pressure. The normal position, when on the New Haven lines, is at position A, inside of the clearance line. To put the shoes "down" ready for third-rail operation, air pressure is admitted to the top compartment, P, of the cylinder, D. The piston, E, is pushed down, also forcing down the lower piston F, to which is fastened the piston rod connected to the shoe. The piston, E, has a definite

travel, and when it reaches the position as shown in Fig. 80 the shoe is in the operating position, indicated as position B; when the shoe reaches position B, it is held there by the latch lever or toggle, G.

When in the "down" or B position, the shoe is tripped by air pressure in the small latch cylinder. A plunger strikes the

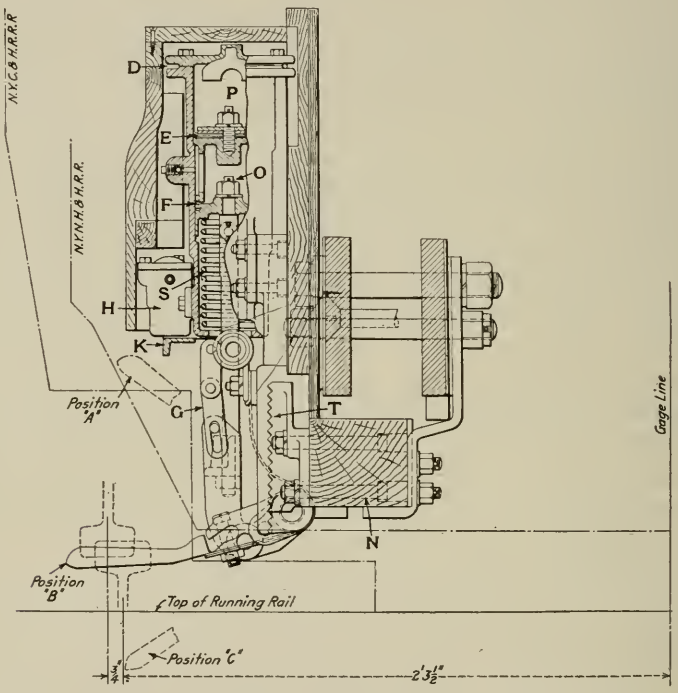


FIG. 80—Under-running—Third Rail Shoe with Emergency Feature.

casting K, pushing the latch back and the main cylinder spring S, then pulls the shoe back to position, A.

The emergency position of the shoe is shown at position C. When the shoe is in the operating position piston, F, has not yet moved its full distance, there still being approximately 1 in. additional movement allowable before the lower edge of the piston will rest against its stop. This extra travel provides an allowance for the emergency position; the shoe is carried to position C, by admitting air pressure in compartment, O, between the two pistons; piston E, is then pushed

back to its normal position and piston F, down to its full travel.

Third-Rail Shoe Leads.—The current is taken from the third-rail shoes into the locomotive by means of electric conductors or cables. These cables do not pass directly into the locomotive, but connect to a fuse box, which may be mounted on the third-rail shoe beam just above the shoes or on the truck, or body of the locomotive. The fuse box is placed in the circuit so that if an abnormal current passes through the

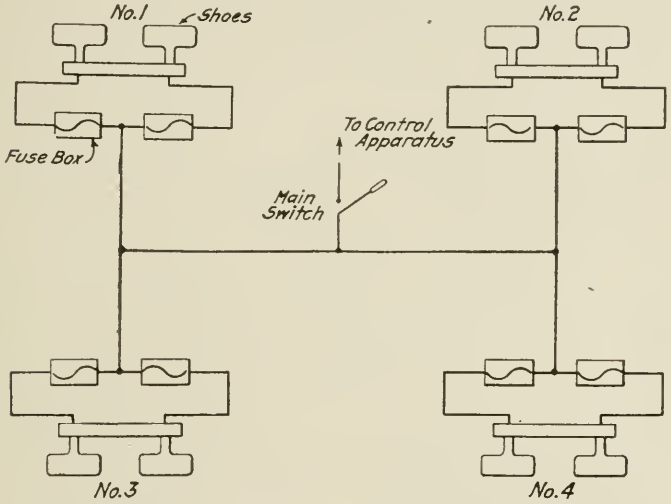


FIG. 81—A Simple Method of Connecting Fuse Boxes. The High-Capacity of the Fuses Required by this Method Reduces the Protection.

fuse, due to a short circuit or breakdown of the main cables and apparatus, the fuses will "blow" and the power will be cut off; damage to the locomotive will thus be prevented. Generally the fuse box is placed as close to the shoes as practicable, thus reducing to a minimum the length of unprotected cable between the fuse box and the shoes.

Generally there are four sets of third-rail shoes mounted on the locomotive, two on either side near each end of the locomotive. By having contact shoes on each side, the locomotive may be operated in either direction, as shoes will always be available on the side toward the third rail. The object in placing them at the ends is to space them far apart, so as to

bridge as large gaps in the third rail as possible. It has been mentioned that gaps in the third rail must occur at cross-overs, intersections, switches, etc., since it is impossible under such conditions to carry the third rail as a continuous conductor. The locomotive must coast over these gaps; with the third-rail shoes spaced at the maximum distance, the time which elapses from the breaking of contact on the rear shoe until the making of contact on the forward shoe, is reduced to a minimum.

There are two general methods used to connect the contact shoes with the fuse boxes and the main conductor leading to

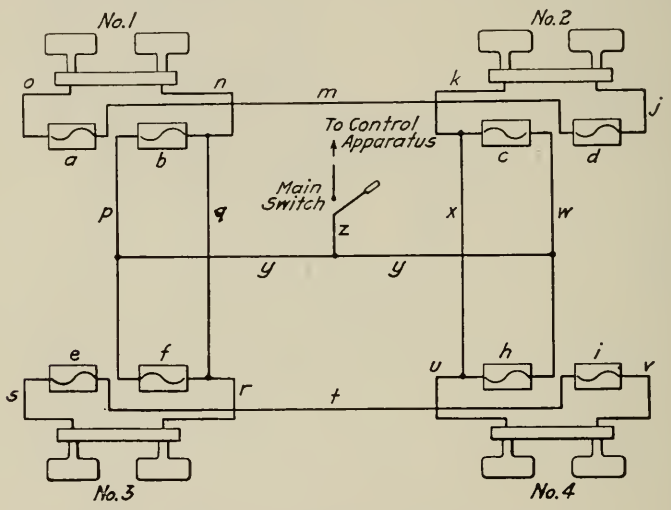


Fig. 82—A Method of Connecting the Fuse Boxes. Which Has the Advantage of Using Fuses of Smaller Capacity and Thus Affords Better Protection.

the main switch. One arrangement is shown in Fig. 81 and the other arrangement is shown in Fig. 82.

Arrangement of Fuse Boxes.—In the arrangement shown in Fig. 81, if the locomotive, in starting, perhaps, has only the No. 1 pair in contact with the third rail, or perhaps the No. 2 pair may have been broken off, then all of the current required by the locomotive must be taken through the two fuses which are connected in parallel. Therefore, the fuses must have sufficient capacity to carry this normal current without blowing. Normally, however, both sets of shoes on

one side of the locomotive are in contact with the third-rail and are collecting current, and, since all the fuses are necessarily of the same capacity, with two sets of shoes collecting current there is really twice the fuse capacity necessary.

A different arrangement is shown by Fig. 82. In this method the shoes on the two sides of the locomotive are interconnected, so that when one shoe is in contact with the third rail, all other shoes are "alive," and the fuse boxes are arranged so that they all are in the circuit. In other words, the electric current taken by the locomotive is drawn through all the fuse boxes on the locomotive, even when only one set of shoes is in contact with the third rail.

With this arrangement, the fuses may be of much lower capacity than if all the current is taken by the locomotive through one fuse, or in some cases two fuses in a parallel.

As an example: with the fuse arrangement shown in Fig. 81, assume that the current taken by the locomotive is 6,000 amperes. Under the conditions existing when only one set of shoes touch the third rail, the single fuse would then require a capacity in excess of 6,000 amperes and would be required to handle this current for the period of time necessary for the locomotive to start a heavy train and until the second set of shoes on the same side came in contact with the third-rail. By connecting the fuse boxes on the side of the locomotive opposite the set of shoes in contact with the rail, as in Fig. 82, the current drawn from the power line by the locomotive is divided among all of the fuse boxes. If four of these fuses were in parallel handling this current, then 1,500 amperes would be the amount passing through each fuse; therefore, a fuse of 2,000 amperes capacity could be used instead of one of 8,000 amperes, as would be required if a single fuse box were used, or 4,000 amperes if two boxes in parallel were used as shown in Fig. 81. With both sets of shoes on one side of the locomotive in contact with the third rail, and with the arrangement shown in Fig. 81, 16,000 amperes would have to flow before the fuses would blow, and thus the protection afforded by the fuses is reduced materially. The capacity of the fuse should not be much in excess of that actually required so that, in case of trouble, the fuses will blow immediately, thus removing current from the locomotive and pre-

venting further damage. In the arrangement shown in Fig. 82, four sets of shoes are shown; the fuse boxes are indicated as *a, b, c, d, e, f, h,* and *i,* and are connected with the third rail shoes and with each other, by the cable connections, *m, n, o* to *y* and *z*. With this arrangement the current taken by the locomotive through the lead, *z*, passes through four fuse boxes *b, c, f* and *h,* regardless of whether one set of third-rail shoes or more are in contact with the rail. Referring to Fig. 82: the No. 1 set of shoes is in contact with the third rail; the flow of the electric current through the cable is then as follows: Current passes up through the cable *n*, part going through the fuse, *b*, along the cable, *p*, and through *y* and *z*. Current also passes along the cable, *q*, to the fuse box, *f*, through the box, and thence to cable, *y* and *z*. The current which passes from the third-rail shoes up the cable, *o*, goes through fuse box *a*, thence to the other end of the locomotive, through fuse box *d*, through cables, *j* and *k*, to fuse box *c*, through this fuse box to cable, *w*, and thence to *y* and *z*. Referring back to cable *n*, the current goes through *q*, as previously mentioned; part of its goes through fuse box, *f*. Cable *q*, also connects to cable *r*, and the current passes thence to cable *s*, to the fuse box *e*, to cable *t*, to fuse box *i*, to fuse box *h*, and then through cable *w* to *y* and *z*. From this it is evident that there are four circuits for the current to pass through, with only one set of shoes in contact.

The Fuse Box.—The fuse box designed for general railway electrification work is of the copper-ribbon magnetic blow-out type. The blow-out arrangement is extremely simple as the copper ribbon fuse itself is the source of blow-out. It is so located, with reference to certain iron parts of the fuse box, that it forms a coil of one-half turn and sets up the magnetic flux necessary to extinguish the arc. With this arrangement, whereby the fuse itself is the source of the blowout, it is obvious that with a heavy current a much stronger blow-out is obtained than with a low current. The capacity of the box is not limited to a heavy current, in fact, it may happen that the arc will be disrupted more easily than with a low current. For the same reason it is usually found that the more severe the short circuit the more easily the arc is disrupted.

The construction of a copper-ribbon magnetic blow-out type

of fuse box is shown in Fig. 83. The body of the box is made of hard white fibre with the back and lids made of non-warping material, or the whole may be moulded from an insulating material.

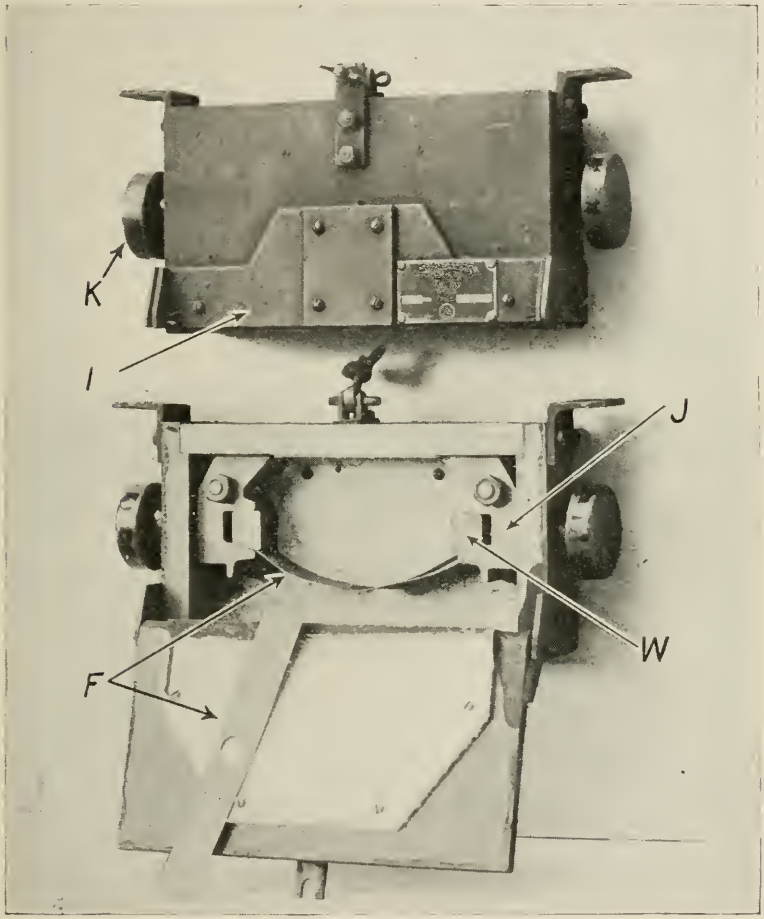


Fig. 83—Railway Fuse-Box Equipped with Magnetic Blowout.

The iron "I" is arranged on the outside of the box and forms the pole pieces and magnetic circuits. It is convenient, although not necessary, to have the lid of the box open as shown in the illustration, as the fuse can be replaced more easily than if the box is solid. The fuse, F, is held in place by

wedge-shaped blocks, W, which are drawn into the jaws, J, by turning the knobs K. The leads carrying the current enter the jaws, J, at the back of the fuse box. The fuses are made of copper ribbon with a hole punched at the center; the amount of metal either side of the hole determine the rating of the fuse and if this rating is exceeded the fuse will blow. The hole determines where the fuse will melt open in case of an overload, and is located at the center so as to have the arc start at this point.

In railway work there is a wide variation in the current used. Fuses for railway service are rated at one-half the current that will cause them to blow in 30 seconds. For instance, a 1,000-ampere fuse is one that will blow in 30 seconds if 2,000 amperes are passed through it. On account of the intermittent load which occurs in railway service, the rated capacity of the fuses which must be installed to take care of the current peaks, is much greater than the equivalent current which they must carry continuously.

CHAPTER XX

THE TRANSFORMER AND AUXILIARY APPARATUS

As has already been stated electric locomotives divide themselves into two classes: those operating on alternating current and those on direct current. While much of the control apparatus is similar in the two classes, there is a decided difference in the scheme of control. First consider the high-voltage alternating-current locomotives and then the direct-current locomotive and point out in the description of the latter wherein the control differs.

The Transformer.—The high-voltage alternating single-phase current is carried from the pantagraph to an oil circuit-breaker which has been described in a preceding chapter. The high-tension circuit breaker is used to connect the power to a transformer, or transformers, as the case may be, these transformers being used to "step down" the high voltage, usually 11,000 volts, to a voltage suitable for the motors and auxiliary apparatus; the auxiliary apparatus consisting of the compressor, the blower and the lights. The construction of this design of transformer is not radically different from any other transformer. However, it has to meet a different condition than does the industrial transformer in that it is subjected to voltage surges, incidental to locomotive operation, and also to moisture where the air-cooled type is used. Heavier insulation must be used on the outside coils and greater creepage distances must be allowed to prevent failure under railroad operation. A few of the earlier locomotives were equipped with oil-cooled transformers, but the air-cooled type is generally used.

Shell type transformers are used for locomotive work. In this type the coils are wound in single sections with square or rectangular copper wire; they are rectangular in shape.

After winding they are clamped, and so held to an exact size during the dipping and drying, which completes the process of manufacture. The copper wire is insulated by paper or cloth, which must be treated so as to become, in effect, a part of the coil. The treatment consists of repeated dipping of the coils in a vat of varnish and drying them in ovens. The var-

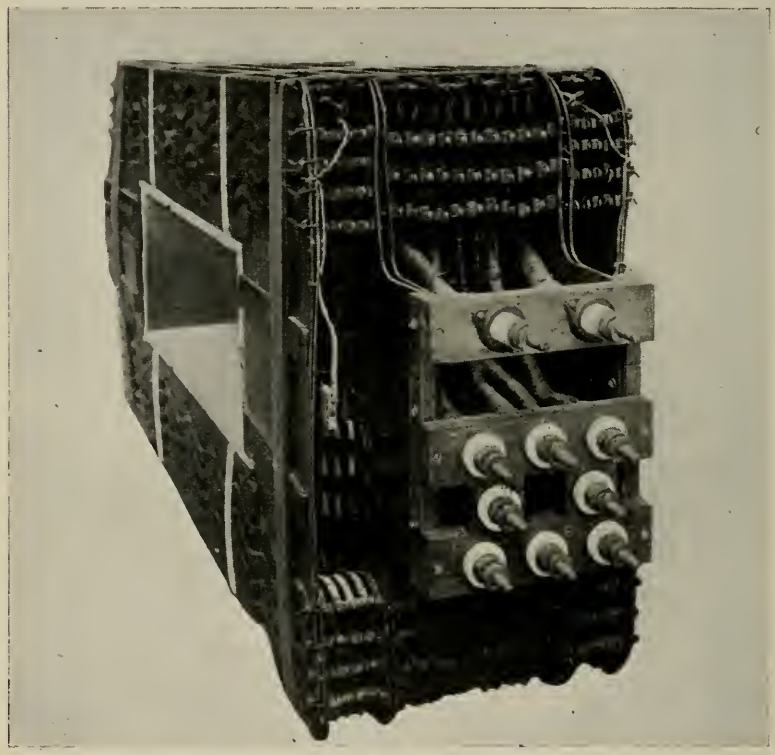


Fig. 84—Transformer Coils and Insulation Assembled and Ready for Applying the Core.

nish is of a special composition, free from any substance which would be injurious to the insulation and especially suited to withstand electrical pressure or voltage, as well as heat. The coils are first thoroughly dried, then dipped in varnish and drained and again dried, this cycle being repeated until the surface is thoroughly coated with varnish; usually about six dippings are necessary. By this process the insula-

tion is thoroughly impregnated, the turns are bound together and the whole insulation strengthened.

These coils are assembled side by side in groups and bound together to make the transformer. It is well known that electric current flowing through copper wire produces heat. In order to get the most out of the copper used, the transformer should be worked at a high temperature, but, of course, not sufficient to exceed the safe heat limit. As electric current flowing through copper produces considerable heat, it is therefore necessary to get rid of the excess heat generated in the transformer coils in order to avoid "burnouts." To do this, the coils, when grouped together side by side, are not placed in contact with each other; strips, inserted between the coils, are so placed that ducts are formed and the heat can be carried away by the air which is blown through. These ventilating ducts must be of sufficient size and number to insure a uniform temperature, and must be correctly located so that hot spots will not exist; if a part of the coil is not properly cooled it will be overheated and cause a burnout.

The spacing strips may be straight—the type used in air-blast transformers—or they may be wavy in form, as used in oil-insulated transformers and shown in Fig. 84. These strips vary in thickness, depending on the size and type of the transformer; an average thickness would be approximately ½ in.

The iron, consisting of punchings of silicon steel less than .02 in. thick in the shell type of transformer, is built around the group of coils, enclosing them entirely. When completed, the transformer has the appearance shown in Fig. 85, the iron forming a shell around the main body of the assembled coils, only the ends projecting. The transformer is enclosed in a sheet iron case, and the air enters at one end and passes out at the other.

The Auto-Transformer.—There are two types of transformers used in connection with electric locomotives; the auto-transformer and the double-coil transformer. At first the auto-transformer was universally used, but lately the double-coil transformer has been generally adopted. The auto-transformer has all of the coils, both primary and secondary, connected together. The high voltage—assume 11,000 volts—is connected to the high tension end, and the other

end of the transformer is connected to the "ground." Starting in at the trolley end with a voltage of 11,000 volts, if it were possible, to follow down along the coils and measure the voltage, the voltage would become lower and lower, according to the distance from the high-tension end, until at the ground connection, the voltage would be zero. It is there-

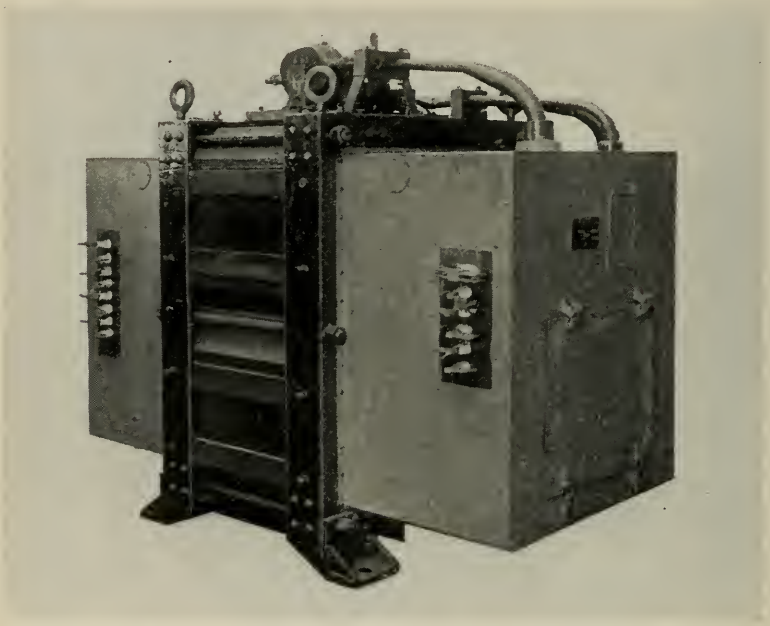


Fig. 85—Complete Transformer Ready for Mounting in Locomotive.

fore possible to get any voltage desired, from 11,000 down to 0 volts, by bringing out a lead known as a tap.

The Double-Coil Transformer.—The double-coil transformer, as the name suggests, has two sets of coils, a high tension set and a low-tension set, which do not connect. The high-voltage coils are connected between the 11,000 volts and ground, while the low-voltage windings are entirely separate and the current is generated in the winding by induction.

The Compressor.—There may be only one compressor and one blower, but it is quite general practice to use two of each. The compressor consists of an air pump of two or more cylin-

ders driven by an electric motor. Power is connected to the motor by a switch thrown by hand. The operation of the pump is controlled automatically by the governor. This governor cuts "in" and "out," depending upon the air pressure in the main reservoir, and "makes" or "breaks" the circuit to the motor. The air compressor is explained in detail in Chapter XVI.

The operation of the motor-compressor differs from the air pump used on a steam locomotive. The steam air pump maintrains practically a constant pressure and, upon the slightest reduction of pressure in the air reservoir, automatically operates to maintain this pressure. In the case of the compressor, the pressure is not maintained at a constant value, but varies between a maximum and a minimum—usually a variation of 10 lb. For instance, the governor is set at a 10-lb. range, and, on locomotives with the feed valve set for 110-lb. train line pressure, the governor would be set to "cut-in" at 120 lb. and to "cut-out" at 130 lb. With this arrangement the compressor is not pumping continuously, but about 50 per cent. of the time.

The Blower.—The blower has been mentioned as one of the auxiliary parts; most electric locomotives are equipped with motor-driven blowers. They are used for furnishing air to the main motors, transformers and any other apparatus which it is desired to cool, and, as the capacity of the motors and other electrical apparatus is determined by the temperatures of the apparatus when operating under load, the blower plays an important part in the service obtained from them. The passing of air through the electrical equipment carries away the heat and allows greater work to be done, which means more electric current. With the installation and use of blowers the capacity of an electric locomotive for a given weight and cost can—within certain limits—be increased by an amount proportionate to the cubic feet of air blown through the apparatus; it is easily possible, by ventilation, to increase the capacity over 50 per cent. The air is conducted from the blower to the various pieces of apparatus through ducts built into the flooring and framework of the locomotive. Two blowers are used on many locomotives so as to keep the size of the blower outfit within reasonable limits, and also to give a better distribu-

tion of air; when more than one blower is used, both blow into the same duct system. Usually the power is connected to, and cut off from, the blower motors by means of small hand-operated enclosed switches, known as canopy switches the same as used in connection with the compressor. To obtain blower operation, it is necessary to have these switches

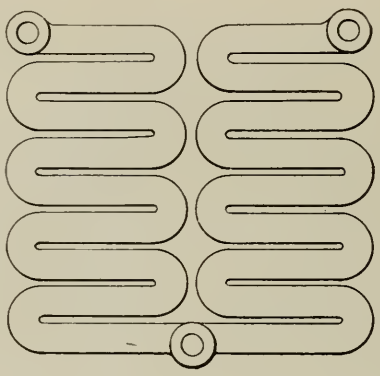


Fig. 86—Single Resistance Grid of Cast Iron.

closed, even though the power is "on" the locomotive. In addition to the canopy switches, an enclosed fuse is inserted in the circuit so that power will be cut off from these auxiliaries in case of trouble, as generally the canopy switches are not automatic and therefore will not open even though the motor may become grounded.

Main Resistance—Grids—For Direct Current.—The resistance is to the direct-current locomotive what the transformer is to the alternating-current locomotive; it regulates the voltage to the motors during acceleration. The main resistance is composed of cast iron resistor grids—Fig. 86—assempled in frames. The higher capacity grids are 12 in. between supporting rods, while the lower capacity grids are only 8 in. These grids are of different sized sections of iron and thus vary in resistance and current-carrying capacity. The grids are assembled on steel tie rods, insulated with mica and supported at each end by steel frames. The frames are provided with lugs and can be bolted securely to the locomotive cab,

The grids may be connected so that they are all in series, or in series-parallel combinations. Mica washers are used between adjacent grids wherever insulation is necessary. In locomotive work where heavy currents flow through the

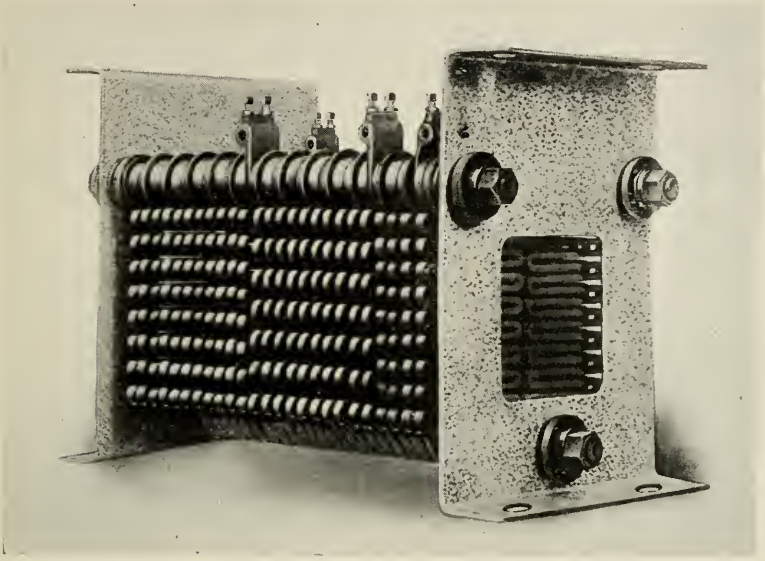


Fig. 87—Resistance Grids Assembled in a Frame.

grids, the bosses of the grids touching each other on the two upper tie rods should be welded together so as to make a good connection, thus preventing a slow deterioration of the contacts which results from the carrying of excessively heavy currents.

Taps are taken off at the desired points by means of terminals which are inserted between two grids. An assembly of grids in a frame is shown by Fig. 87.

The Water Rheostat.—It can be readily understood that in the case of large powerful electric locomotives, especially those designed for freight service, the resistances required would necessitate apparatus that would be rather large and heavy and occupy much space. Locomotives in heavy mountain freight service may be required to stand still, with cur-

rent on, for a period as long as two minutes, endeavoring to start the train. Operation of this kind places a severe stress on the resistances and these conditions, together with the limitations of the grid type of resistance, have been responsible for the development of the water rheostat for use on electric locomotives. The principle involved in their design is not new. Water rheostats are in common use in connection with test apparatus. In this type of rheostat the electricity is passed between metal plates submerged in water in which sodium sulphate has been dissolved. Pure water is practically a non-conductor of electricity, but when an impurity is added large quantities of electricity can be passed through the solution. The amount of current which will flow depends on the size of the plates or the area immersed in the solution, and on the distance between these plates; the resistance can be gradually cut out by increasing the area of the plate immersed and also by bringing the plates nearer together. Thus the change from total resistance to zero resistance can be made gradually, there being no definite "steps" as in a group of grid resistors. Where electrical energy is lost in resistance, heat is developed; this is true of the liquid rheostat so provision must be made for circulation and cooling of the liquid to prevent rapid boiling away of the solution. Such a type of rheostat is used on the powerful electric locomotives operating over the Elkhorn Grade of the Norfolk & Western.

The Control Circuit.—The circuit arrangements of the first electric locomotives were similar to those used on trolley cars in that the main leads from the motors were run to a controller in the engineer's cab. The circuits were made and broken in this controller as well as the motor combinations, so that the main currents were handled by fingers sliding over drum contacts. This arrangement in connection with trolley cars is entirely satisfactory, but far from satisfactory for locomotive operation. In fact, with the growth of the locomotive to larger and larger sizes some other method was necessary. The enormous currents now used by electric locomotives require a large amount of apparatus to connect the main leads with the motors and to provide a means for connecting the motors in the proper combinations for operation

forward and backward at different speeds. The mechanism necessary to meet these conditions is designated as control apparatus, and, as it must be under the control of the engineer, located at the head end, some form of remote control arrangement must be provided.

There are two distinct systems which have been used for this purpose:

(a) The electro-pneumatic system.

(b) The electro-magnetic system.

The electro-pneumatic system is in use in all of the locomotives on the New Haven, the Pennsylvania, the Norfolk & Western and many others.

In the operation of this system, air, which is available on the locomotive, is used as the power for closing contacts or switches which, in turn, connect the power to the motors. The switches are controlled by means of control circuits; the power for the control circuits is taken from an independent source, a storage battery having a voltage of from 20 to 32 volts, being furnished for this purpose.

A detailed description of this system is given in the next chapter but as these storage batteries must be kept properly charged, before describing the control apparatus, the two different types of battery circuits or arrangements which are used with the electro-pneumatic system will be described and the manner in which the recharging is accomplished will be outlined.

Charging the Control-Battery—D. C. Locomotive.—In the direct-current locomotive, the charging is easily taken care of by connecting the battery on the ground side across a resistance in the circuit of the motor-driven compressor. A diagram of connections for battery charging with direct current operation is shown by Fig. 88. There are two batteries, each of which is connected to a double-pole, double-throw, knife switch. These switches are cross connected so that either battery can be charged or connected to the control circuits. The negative side of the compressor is connected to the coil of the relay R, known as the battery charging relay, and then to the battery charging resistance. When the governor closes and the compressor operates, the current passes through the

relay coil to point, A, on the resistance, and thence through the resistance to ground.

The current energizes the relay, causing the plunger to pull up the connecting points *b* and *c*. With the switches open, as shown in Fig. 88, there is, across the terminals, + and —, a voltage equal to the voltage between point, A, and ground. A current flowing through a resistance gives a voltage drop, and this voltage drop will depend on the position of A; the voltage will be increased as A is moved further away from the

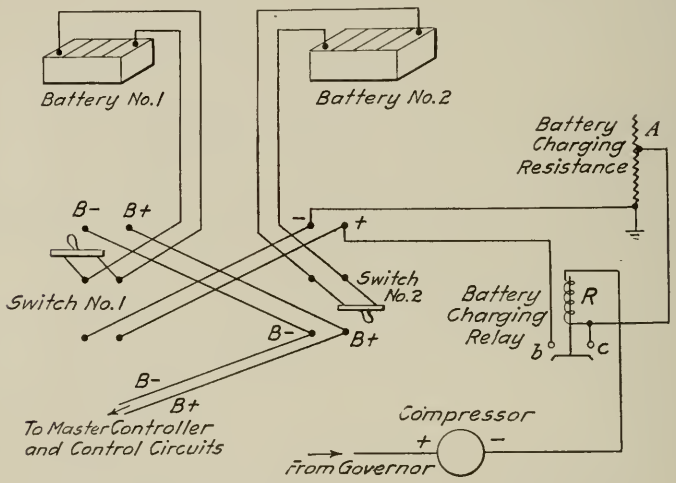


Fig. 88—Diagram of Connections Used for Charging Batteries Used on Direct-Current Locomotives.

ground end. Thus a voltage can be obtained which is suitable for the type of battery used.

As previously mentioned, two batteries are used, each connected to a double-throw switch at the hinge terminals. The other terminals are marked B+ and B—, and connect to the control wires running to the master controller. With both switches in the "up" position, No. 1 battery would be furnishing to the B+ and B—, power for operation of the control, while No. 2 battery would be connected across the battery charging resistance whenever the compressor operates. With the switches in the "down" position No. 1 battery would be connected across the resistance, receiving the charging current, while the No. 2 battery would be supplying the power for

the operation of the control. With two batteries, it is possible to charge one battery while using the other, and, by throwing the switches "up" and "down" on alternate days, the batteries can be kept in first-class condition.

Charging the Control Battery—A. C. Locomotive.—The arrangement of batteries shown in Fig. 88, is not possible with locomotives using alternating current as the passage of alternating current through the batteries would not charge them. Therefore another arrangement—see Fig. 89—is necessary and a small motor-generator set is used. It consists of a motor direct-connected to a generator; the motor is of the alternating-current type, and is connected to one of the

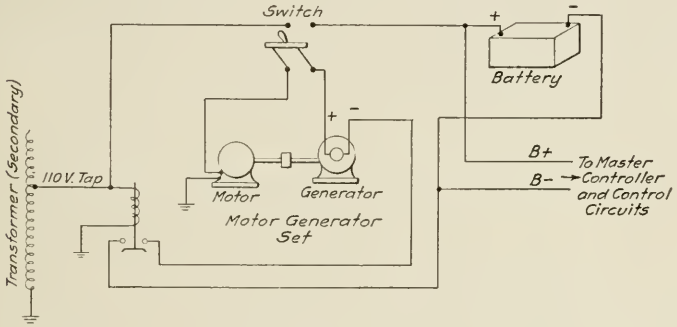


FIG. 89—The Connections Generally Used for Charging the Control Battery on an Alternating-Current Locomotive.

transformer taps of suitable voltage; the generator is of the direct-current type, wound to give a voltage suitable for charging the battery. While some alternating-current locomotives are provided with two batteries interconnected so that they can be used on alternate days, it is only necessary to have one battery.

In the arrangement shown in Fig 89 a tap is taken from the transformer at approximately 110 volts, and is connected through a line relay to ground. The tap is also connected to one side of a double-pole single-throw switch. When this switch is closed the 110-volt current is connected to the motor of the motor-generator set, which will operate whenever power is "on" the transformer. The other side of the switch is connected in the generator circuit. The current from the generator will pass through the switch to the battery, through

the battery to the line relay contacts, through these contacts and back to the generator. The object of this line relay is to prevent the battery feeding back into the generator and running the generator as a motor when the power is cut off from the transformer and the switch left closed. The leads to the master controller are tapped on as shown.

When operating, the generator furnishes power to the battery, and to the control, in multiple. In other words, the battery is "floating" on the line. It is being charged whenever the power taken by the control circuits is less than that delivered by the generator: The generator supplies the power to circuits whenever the motor-generator set is running, and the battery is only for emergency purposes to take care of extraordinary demands or to supply current to the control when the set is not running.

CHAPTER XXI

THE CONTROL APPARATUS

In the preceding chapters the electric current has been traced from the third-rail shoes to the main switch in the case of the direct-current locomotive, and from the overhead trolley, through the pantagraph, the high-tension circuit-breaker and the transformer, in the case of the alternating-current locomotive. In order to connect the electric current to the motors and to provide a means for connecting the motors in the proper combinations for operation forward and backward at different speeds, methods of control have been developed which require the use of apparatus designated as control apparatus, or control system.

Control Systems.—As previously stated two distinct systems of control have been used—the electro-pneumatic system and the electro-magnetic system; the electro-pneumatic system has become the universal system. As the name implies, air pressure, which is available on the locomotive, is used to close the switches. The air pressure to, and the exhausts from the various switch cylinders is regulated by small magnetic valves which are remotely controlled. These circuits are called the "control circuits," and power to them is usually supplied from a storage battery having a capacity of from 20 to 32 volts. The general arrangement is as follows: The battery power is connected to the master controller, which corresponds to the engineer's throttle on the steam locomotive and which is shown by Fig. 90. This master controller is located adjacent to the air brake valve and provides the means for connecting the battery current to a system of control wires which run from the master controller to the unit switches. The energizing of one of the control wires operates a small air valve, allowing the air pressure to enter

a cylinder, moving the piston, and thereby closing the switch. The power from the main circuit is connected to the switch, which, upon closing, throws the power on the motors.

The electro-magnetic system does not make use of air pressure for closing the switches, but depends on the electric power. The power for closing the contacts or switches is obtained from the magnetic pull of a solenoid through which is flowing an electric current of small value. The arrangement of the control circuits in this system is somewhat the same as in the electro-pneumatic system, except that high voltage

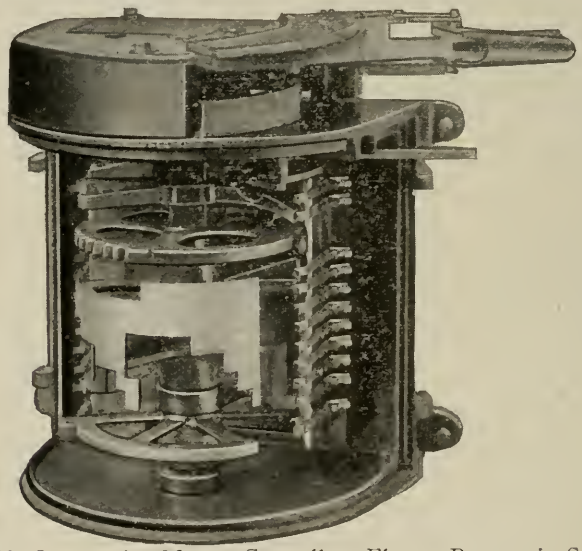


Fig. 90—Locomotive Master Controller—Electro Pneumatic System.

of 600 volts is used instead of low voltage from a battery. There are systems using higher voltages than 600 on the third rail or overhead wire—1,200, 2,400 and 3,000 volts—but in each case provision is made to reduce this voltage to approximately 600 volts for the control circuits. A tap is made to the main supply—if of 600 volts—and connected to the master controller. The master controller is composed of fingers and a drum, and as the drum is rotated the power is connected to the wires leading to the solenoids in the switches. The master controller is slightly different from the one used with the electro-pneumatic system, as it handles a larger current per

finger and a higher voltage. The creepage distances must be greater and the fingers larger. The flow of current through the solenoid, creates a magnetic field and the pull of this field is applied to operate and close the switch by means of a plunger connected to the movable jaw of the switch and extending into the core of the solenoid.

Electro-Pneumatic System.—In the design of the electro-pneumatic control which is in extensive use, the switches are grouped together in numbers varying anywhere from 6 to 12,

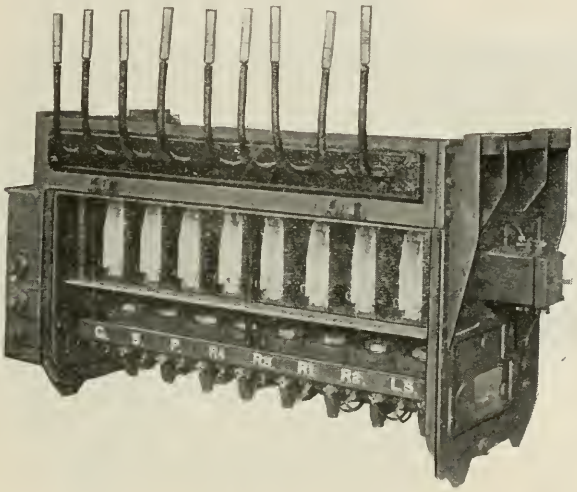


FIG. 91—A Switch Group, Front View.

or even more—called a switch group. An arrangement of this kind is very convenient as each switch is a unit and is interchangeable with any other switch. Moreover, by grouping the switches, many connections between switches can be made by permanent copper straps and only the leads leave the group for connection to other groups or to the motors. Such a group of switches is shown in Figs. 91 and 92. The strap connections from one stud to the other are clearly shown in the proper sequence. One of these unit switches is illustrated in the sectional view Fig. 93, and in Figs. 94 and 95.

The air is piped into the end of the group at 70-pounds pressure and fills the pipe reservoir running the whole length of the group. Each of the cylinders and magnetic valves re-

ceives air from this reservoir through the air connection bushing, 40. Gaskets 39, are used to prevent leakage of air. The 70 pounds of air pressure is therefore always available around the head of the lower valve, 16, which is held on its seat by the spring, 17. When the engineer operates the master controller, thereby connecting the battery voltage to a control wire, the battery current flows through the wire to the terminal, 14,

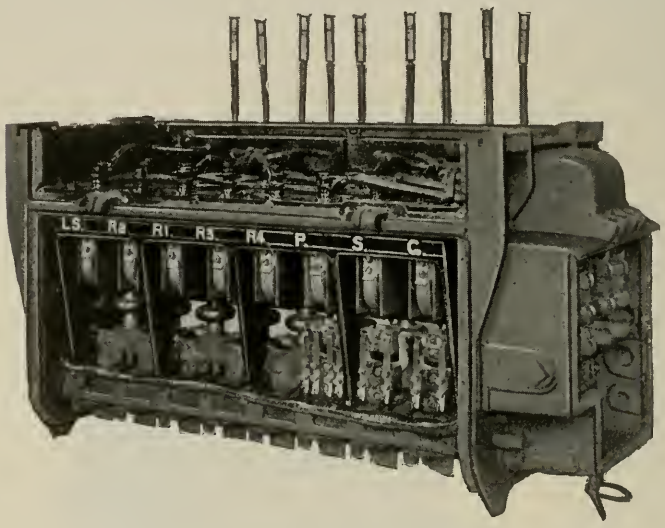


Fig. 92—A Switch Group—Rear View, Showing Studs and Strap Connections.

through the magnet coil and out of the other terminal—not shown—back to the battery. The battery current flowing through this coil magnetizes the core, so that armature, 7, is drawn down. As shown in the cross section, armature, 7, rests on top of the upper valve stem, 15, so that when the armature is drawn down, the upper valve stem pushes the lower valve, 16, away from its seat. The air pressure of 70 pounds can then pass up through the opening into the passageway leading into the cylinder, and, entering the cylinder compresses the heavy spring and pushes up the piston rod, forcing the switch contacts together and establishing the main circuit connection.

The switch will stay in contact as long as the magnet is energized and there is sufficient air pressure to compress the

spring. When the battery voltage is disconnected from the control wire the coil is no longer energized, there is no pull on the armature and the lower or inlet valve closes on its seat due to pressure of the small spring, 17. Air pressure is thus cut off from the passageway leading to the cylinder. The lower end of the upper valve steam, 15, forms a valve and when pushed down by the armature closes the opening from the air

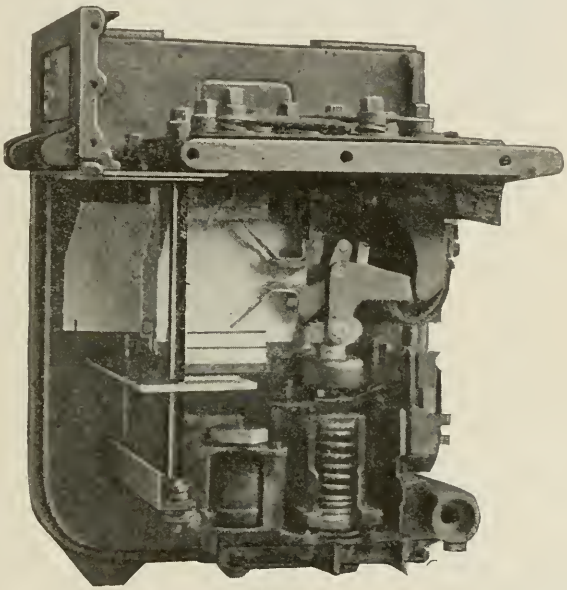


Fig. 93—Assembly of a Unit Switch.

passageway to the exhaust port. This is the exhaust valve seat, so that when the coil is energized and air pressure is admitted to the cylinder, it is retained in the cylinder, and when the battery voltage is disconnected from the coil and the valve stem returns to its normal position the air in the cylinder can pass out to the atmosphere through the exhaust port. The air is expelled by means of the heavy spring in the cylinder and the main contacts are opened rapidly.

The packing, 19, used in the cylinder to prevent "blowing-by" of the air pressure, consists of triple leathers, each leather being specially treated and specially formed to cup shape. The packing is backed up by a steel follower 46, also cup shaped, and an expander, 47, is used on top of the packing so

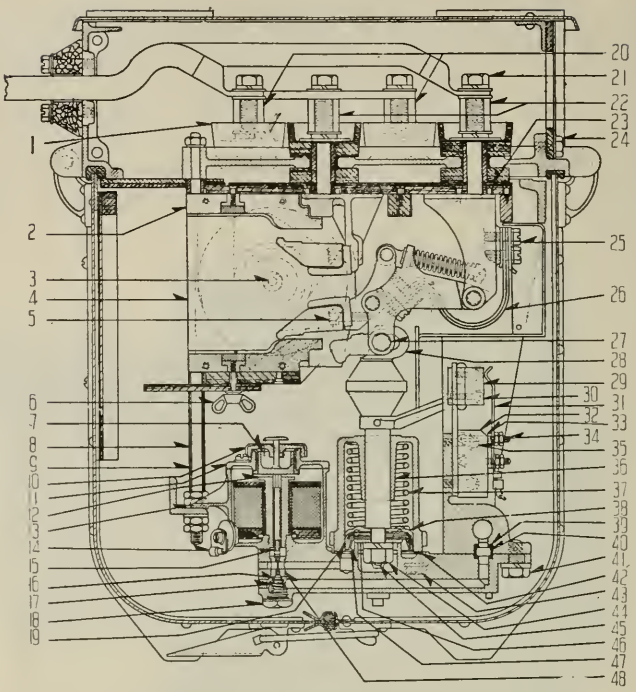


FIG. 94—Cross-Section of Unit Switch—Electro-Pneumatic System.

NAMES OF PARTS OF FIG. 94.

1 Insulating washers.
2 Arc chute.
3 Blowout coil.
4 Arc chute side.
5 Bolt holding switch contacts.
6 Wing nut holding arc chute in place.
7 Armature of magnet valve.
8 Bolt for angle iron supporting valve magnet casting.
9 Tube of insulation.
10 Magnet valve cap.
11 Magnet valve iron cover.
12 Magnet valve core.
13 Magnet bracket support.
14 Terminal of magnet coil.
15 Upper valve stem.
16 Lower valve stem.
17 Valve spring.
18 Plug.
19 Piston packing-triple leathers.
20 Tapped head terminal bolts supporting blowout coil.
21 Stud bolt.
22 Terminal bolts supporting switch.
23 Screws holding switch parts to box.
24 Screws holding cover.
25 Bolts holding shunt.
26 Copper braided shunt.
27 Pin which engages in hook.
28 Hook.
29 Interlock block.
30 Screw holding block.
31 Interlock finger.
32 Interlock finger base support.
33 Interlock finger base.
34 Bolts holding interlock fingers.
35 Screws.
36 Piston rod guide.
37 Cylinder spring.
38 Piston.
39 Gaskets for brass air connection bushing.
40 Brass air connection bushing.
41 Supporting bolt magnet valve bracket.
42 Gasket for air cylinder.
43 Bolts holding cylinder in position.
44 Nut holding piston details in position.
45 Cotter pin.
46 Piston follower.
47 Expander.
48 Valve bushing.

as to keep the leathers in the correct shape and against the cylinder wall.

The cables leading from the motors and resistance connect to the stud bolts, 21. These studs pass through the top framework of the switch group, being insulated therefrom by means of washers and a tube made of insulating material. The studs screw into the copper castings one of which is stationary and to which is bolted a copper contact, while the other is composed of a movable arm, to which is bolted the

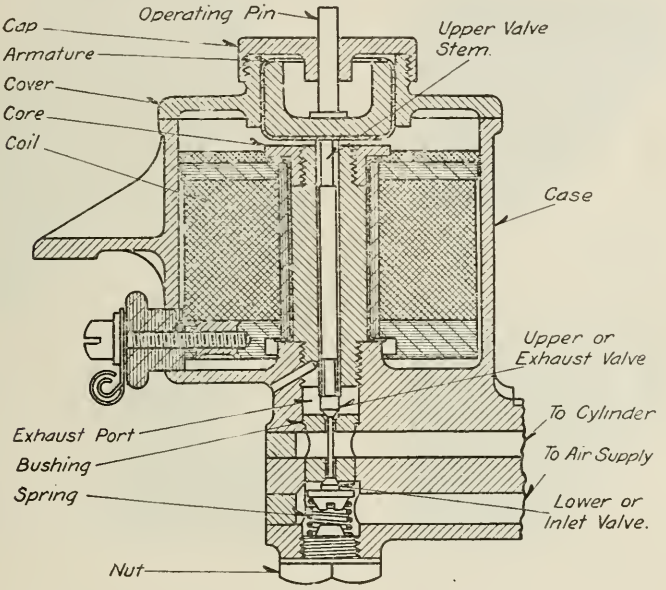


Fig. 95—Cross-Section of a Magnet Valve.

other contact. The main current enters and leaves the top of the group while the main circuits are entirely independent of the control circuits. The end of the piston rod carries an insulator, in order to insulate the power voltage from the control apparatus. The hook, 28, on the upper end of the piston rod engages with the movable arm thus closes and opens the main contacts. The bolts 5, used for bolting the contact tips in place, also hold in position strips of copper called arcing horns which project beyond the contact points. As the name suggests they are used to take care of the arc which forms when

the contacts open, breaking the main circuit current. The arc which is formed across the tips of the contact is carried out along arcing horns, becoming of greater and greater length, and when it reaches the end of these horns it is blown out

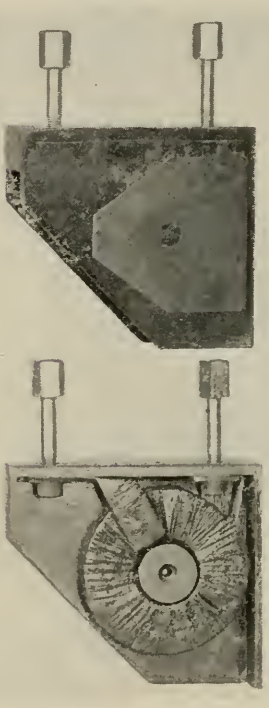


Fig. 96—A Blow-Out Coil.

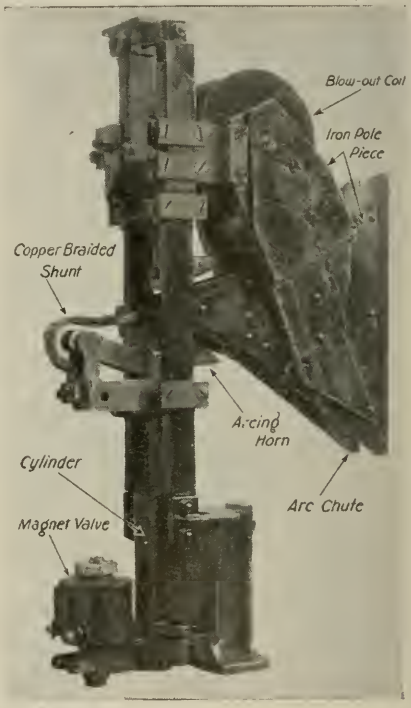


Fig. 97—A 3000-Volt Large Capacity Electro-Pneumatic Switch.

and the circuit is interrupted. To aid in the rapid disrupting of the arc blow-out coils are used. As shown in Fig. 91 and 92, there are spaces between each of the switches. This space is occupied by a blowout coil, details of which are shown in Fig. 96. The blow-out coil consists of a few turns of copper strap and the connection to it is made by the studs as shown. The arrangement of main circuits is such that the current flows through these blow-out coils before it passes through the switches. With this arrangement the contacts open and an arc is formed, with the current still passing through the blow-

out coils. A magnetic field exists across and at right-angles to the arc between the contacts, so that according to the laws of magnetism and electricity the arc moves in the magnetic field, and is blown out magnetically, almost instantaneously.

Considerable heat is formed with repeated opening of a pair of contacts and the arc is confined in an arc chute having the removable sides shown in Fig. 93 and by 4 in Fig. 94. To carry the current from the movable contact and around the point of support, to eliminate heating, a copper braided shunt, 26, is provided, which bolts directly to the copper casting and the contact block. The construction of the movable arm is such that, as the contacts are pressed together, there is a wiping action to insure good contact.

A 3000-volt large capacity electro-pneumatic switch as used on the Chicago, Milwaukee and St. Paul locomotives is shown in Fig. 97. The construction and assembly of this switch is somewhat different. Each switch is a complete unit. The blow-out coil is self-contained with the upper contact and is not separate from the switch. In order to get sufficient insulation and prevent creepage the parts must be spaced much farther apart than for low voltage operation.

Electro-Magnetic System.—The construction of the electro-magnetic switch is as follows: Inside of a soleniod projects the core or plunger, the lower end of the plunger being connected to a switch arm. The control current flowing through the turns of wire of the solenoid creates a magnetic field which pulls the plunger further into the solenoid, raises the switch arm and brings the contacts together, completing the circuit for the main power.

A spring is located between the switch arm and contact piece, the latter being movable in relation to the arm. When the plunger is drawn into the solenoid the contacts are brought together and, as more pull is exerted, the spring is compressed, giving a rocking motion to the lower contactor. This scheme is similar to that embodied in the electro-pneumatic switch and is very essential for successful operation of the electro-magnetic system. This movable lower contractor remains in contact even after the plunger has dropped out a little way, but the point of contact has shifted from the heel of the contactor to the front half. When the contactors

separate, the arc which exists until blown out is at the front part of the contactors and thus the burning of the copper does not take place on the part of the contactors which are

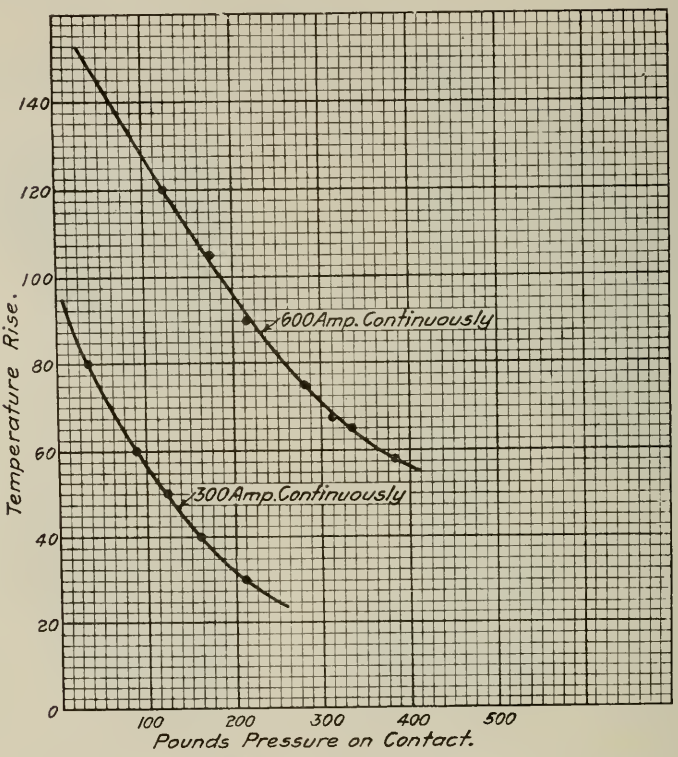


Fig. 98—Curves Showing Relation Between Current-Carrying Capacity and Pressure on Contacts.

together when the switch is fully closed and through which the main motor current passes. Acting horns are provided to carry the arc to the front of the box and a blow-out circuit is provided to blow out the arc electrically. Shunts are used to carry the current around the various hinge pins.

Advantages of the Electro-Pneumatic.—The electro-pneumatic system of control has been universally adopted and it is now considered the standard. The electro-magnetic system has been used considerably but it has certain disadvantages not encountered in the electro-pneumatic system. The

electro-pneumatic system has the advantage that the switches are operated by air and a constant pressure is thus obtained between the contacts carrying current, independent of what the voltage on the third-rail may be.

With air, any desirable pressure can be obtained at the con-

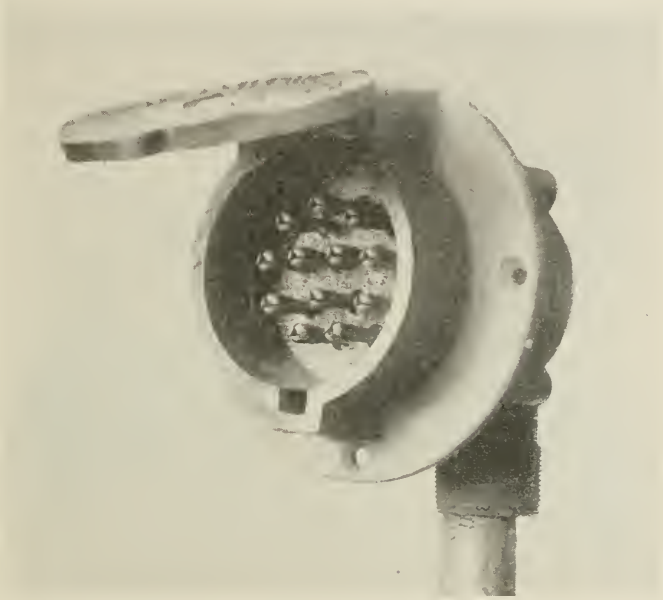


Fig. 99—A 12-Point Train Line Receptacle.

tacts; the air pressure supply can be varied, or the size of the switch cylinder can be varied. It has been found that the amount of current that can be carried by a pair of contacts, for a given temperature rise, depends on the pressure between the contacts. The greater the prssure the more current can be carried for a given temperature rise, and therefore the temperature rise will be less with a given continuous current.

An idea of what the pressure between a pair of contacts 1 in. wide means, is shown by Fig. 98; these curves show how the capacity of the contacts can be increased. For example, at 90-lb. pressure on the contacts, with 300 amperes flowing, there is a temperature rise of 60 degrees C., but if the pressure is increased to 365 lb. the contacts will carry 600 amperes continuously for the same temperature rise. Again with

365-lb. pressure the temperature rise is 60 degrees C. but if the pressure is reduced to 255 lb. the rise will be 80 degrees C.

In the case of the magnetic switch, it is closed by a solenoid, so that if the voltage to this solenoid reaches too low a value, the pull of the solenoid will be decreased, and the pressure will be less. On heavy traction systems that is not much of a factor, as the third-rail voltage is usually nearly constant

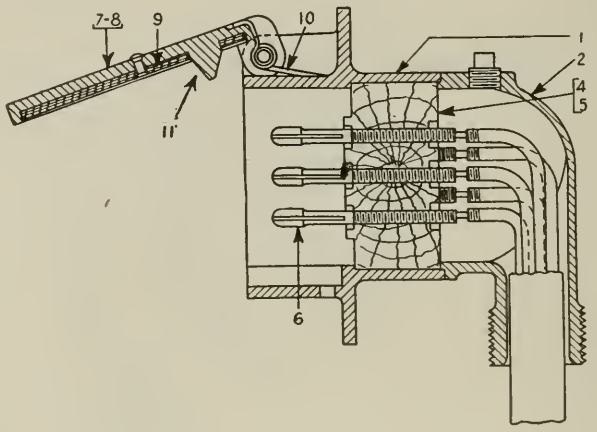


Fig. 100—Cross-Section of Receptacle.

and does not drop appreciably with heavy loads. On smaller systems, where the feeder supply is not on the same basis, the voltage may be reduced considerably. The low voltage occurs at the time that maximum current is flowing through the contacts, so that there is liability of the contacts becoming "frozen" or welded together.

Another advantage of the electro-pneumatic system is that the control circuit is of low voltage. A storage battery, usually of 32 volts, supplies the power for operation of the electro-pneumatic switches. All of the control circuits are at this voltage and all forms of interlocking can be readily used. With the electro-magnetic system the 600-volt supply is generally used for the operation of the solenoids and the control circuits. All of these circuits are amply protected by fuses, but the low-voltage control circuit is more desirable.

Locomotive Control Connections.—The engineer, sitting at the front part of the electric locomotive has complete control

of the switches and auxiliary apparatus and hence the control of the locomotive through the master controller.

For example, on an electric locomotive equipped to operate on both alternating and direct current, with pantagraph for collection from the overhead trolley wire and with shoes for collection from the third-rail, the raising and lowering of each of these types of current collectors is under control of the engineer. Air pressure is used to operate the third-rail shoes or the pantagraphs, and this air pressure to the operating cylinders is controlled by magnetic valves, which in turn are

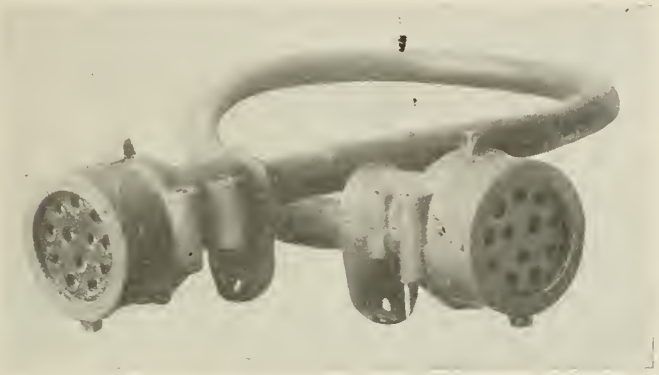


Fig. 101—A 12-Point Jumper.

controlled by push buttons located on or adjacent to the master controller. The battery current passes through the contacts of the push button, when closed, and energizes a valve similar to the valve described for the unit switch.

A means is also provided so that the circuit breaker can be reset automatically, when it has opened due to overload caused either by too rapid notching up of the controller, or to a failure in some part of the main circuits. The battery current is connected to a small trip-coil which unlocks the overload trip, returning it to its normal position so that the battery current can again energize the magnet valves used to close the circuit breaker switches. When resetting the circuit breaker the master controller must be thrown to the "off" position so that the breaker can not be reset with the switches closed and in an operating position. This condition could

exist with the locomotive at a standstill unless such a means of interlocking was used.

With the large number of control circuits required for the operation of an electric locomotive, the wiring at first seems complicated but after the principle is understood, it is comparatively simple. These control wires are led to the various pieces of apparatus from the master controller. For each installation, junction boxes are provided where connections

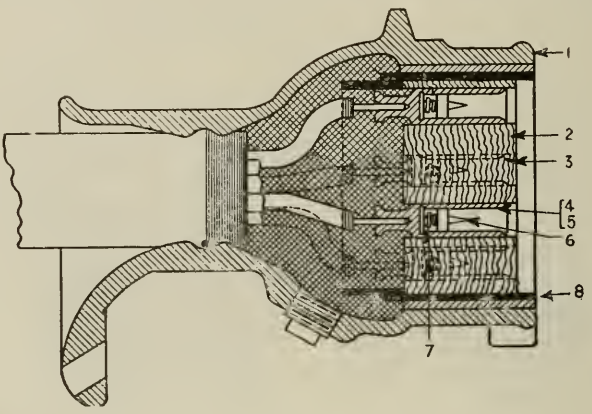


Fig. 102—Cross-Section of Jumper Head.

are made to these wires from the master controller and which are known as train line wires.

This feature of control affords another of the advantages of electric locomotive operation—the possibility of operating locomotives as double headers, under the control of one man at the front end. To accomplish this, the control wires must pass from the head locomotive to the rear locomotive, so that when a particular wire is energized it not only brings in a certain switch in the leading locomotive but the same switch is brought in, in the rear locomotive. The train line wires are carried to the rear locomotive by train line receptacles, Figs. 99 and 100, and jumpers, Figs. 101 and 102. The jumpers plug into the receptacles and carry the control wires across the space between the two coupled locomotives.

CHAPTER XXII

CONSTRUCTION OF THE MODERN RAILWAY MOTOR

In previous chapters—Chapters VI, VII, VIII—the fundamental electrical principles which govern the operation of the various types of electric motors suitable for railway service, have been discussed. In the application of these principles to the supplying of power to locomotive driving wheels, the mechanical features of the design of such essential parts as the frame, the housings, the poles and field coils, the armature

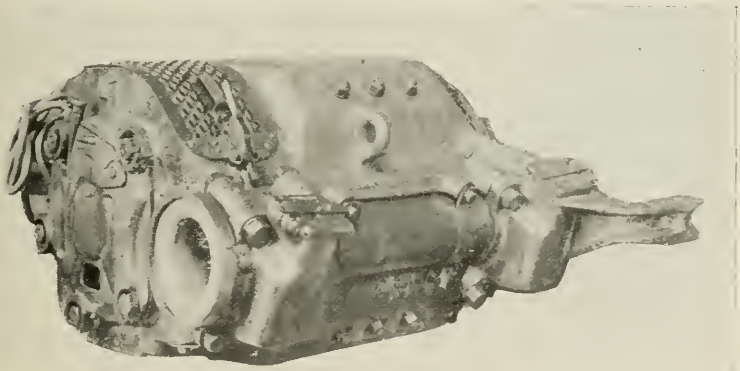


FIG. 103—A Large Railway Motor Completely Assembled and Ready for Mounting on Truck.

and the brush-holders, deserve attention. Each of these parts will be considered separately and as a whole.

The Frame.—The frame is a steel casting upon which the electrical and mechanical parts are assembled and varies in shape and size, depending upon the type of drive, i. e., the mechanical connection to the drivers, and the horsepower rating of the motor. Lugs or feet are provided for fastening the frame to the locomotive and bearings in which the axle,

or a quill surrounding the axle, rotates, are generally necessary to keep the proper alignment of the motor. The design of the frame does not change the electrical characteristics; the magnetic field strength and the number of armature conductors, etc., determine the speed and torque of the motor.

In general the design of the motor is the same for all arrangements and sizes so that a description of the construction of a 200-h.p. motor, of the type which is used on subway equipment is typical of all railroad work and will explain fully

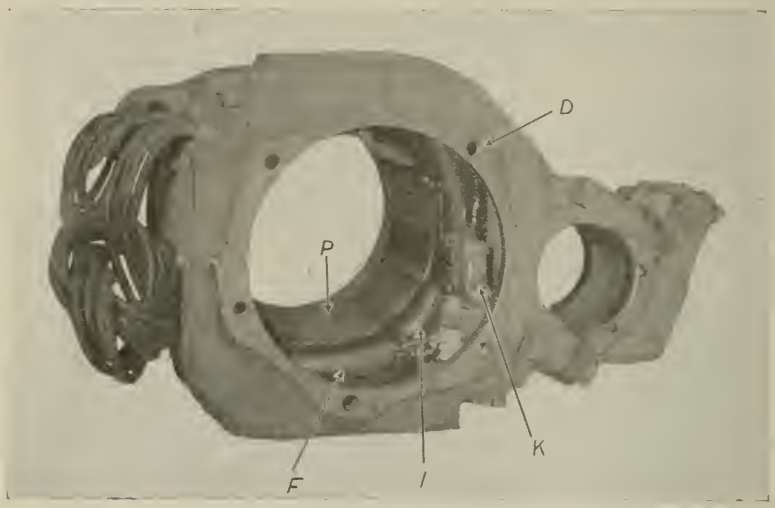


Fig. 104—Motor Frame with Housings and Armature Removed.

the problems to be met. Such a motor is shown in Figs. 103 and 104.

In Fig. 104 the ends or housings, which carry the armature bearings and support the armature centrally with the bore, have been removed by removing the bolts at D. The assembly and relative position of the fields and pole pieces are thus clearly shown. The main field coils, F, which surround the laminated pole pieces, P, furnish the magnetic circuit for the operation of the motor. Between these main fields are located the interpole coils, I, surrounding small pole pieces and furnishing a magnetic flux to improve the commutation and prevent flashing under heavy load and high speed conditions. The brush holders, K, are shown equally spaced around the

frame and so located that when the armature is assembled in the frame the carbon brushes, carried in the holders, will bear on the commutator.

In the construction of the motor the center line of the armature must bear a definite relation to the bearings at the axle. After locating the centers in respect to the axle bearing, the frames are bored out to the correct inside diameter. This bore does not cut material from the whole inside surface of the casting but only from the poles which project a few

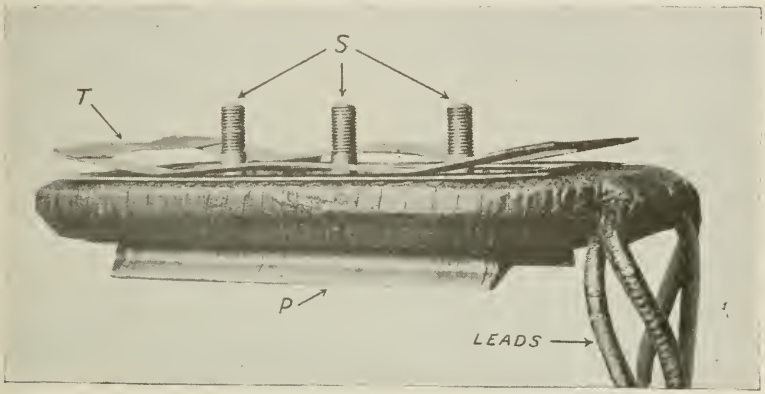


Fig. 105—A Main Field Coil with Pole Piece.

inches above the rest of the casting. The bore for the housing is also made, holes drilled for securing to the frame and the part faced. Holes are drilled to jig through each pole piece to the outside of the frame, through which the studs on the pole pieces pass, with nuts and lock washers to hold them tight.

Pole Pieces and Field Coils.—The motor is now ready to assemble. The main field coils, Fig. 105, and interpole coils, Fig. 106, are each made up of copper strap of several turns, each turn being insulated from the other and all entirely covered by insulation, are slipped over the pole pieces P and the pole pieces bolted to the frame by stud bolts S. A piece of spring steel T is placed behind the coil and next to the frame to prevent all vibration and to take up for the shrinkage of the field coils. Some of the leads from the coils are connected to adjacent coils or brush holders and others are carried

through holes in the frame, the holes being fitted with bushings to protect the leads. The main pole pieces are not solid but are made up of laminations which are held between two end plates riveted together when the laminations are under a pressure of 60 tons or more.

The Housings.—The housing is illustrated by Fig. 107 which shows an exploded view of the bearing and the method of lubrication.

The lubrication of the armature and the axle bearings are

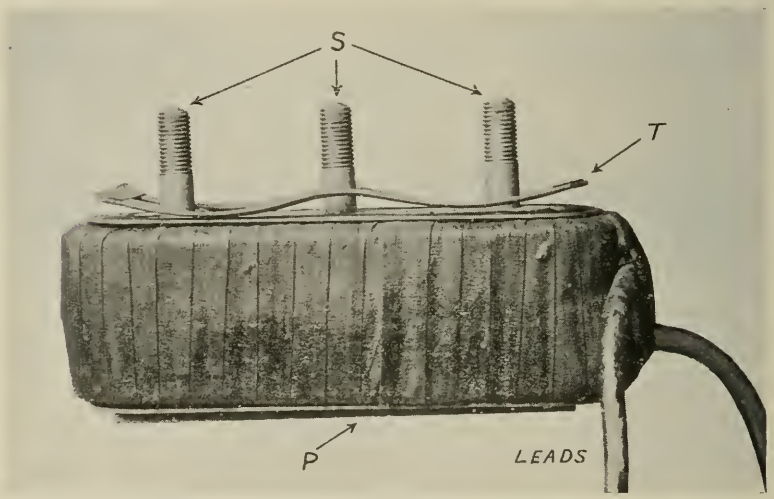


Fig. 106—An Interpole Coil and Core.

important, especially the former, for if the armature bearing should become overheated and the lining of babbit should melt it would allow the armature to drop a distance sufficient to bring the armature onto the pole pieces, as the air gap between the armature and the pole faces is small.

The housing is provided with a separate oil pocket into which the oil is poured from time to time as needed. This pocket provides a means of gaging the amount of oil in the bearing, which should be kept at such a level that it will be carried up to the armature shaft through the packing waste by capillary attraction. Thus the oil is filtered before it reaches the axle and there is no dirt or grit which reaches the bearing. After the oil passes through the bearing and

comes out at the back or inside end, it runs into openings in the housing, which drain into the overflow pocket from which it can be removed when the locomotive is in for inspection

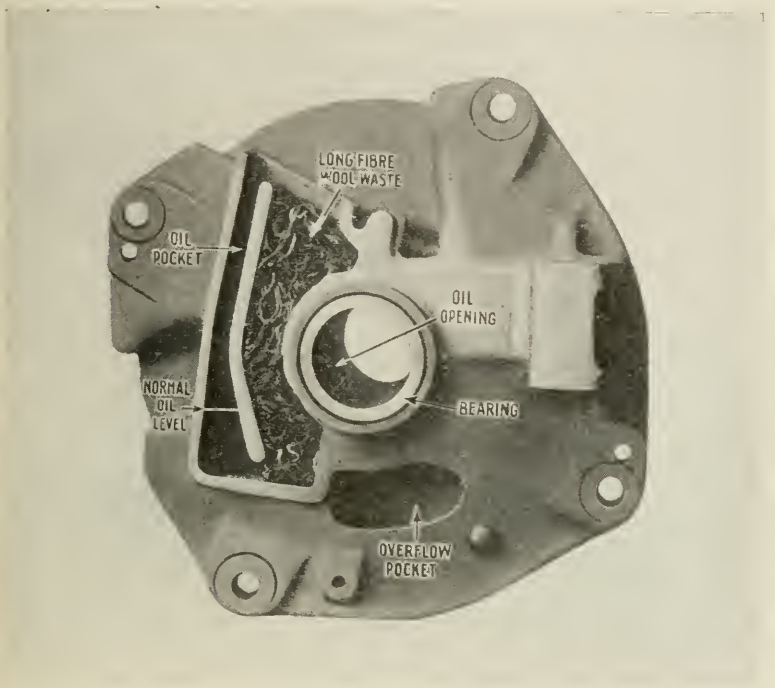


Fig. 107—An Illustration of the Arrangement of a Motor Housing, Bearing, and Method of Lubrication.

and either used for outside oiling or cleaned and filtered and used again on the motor.

The Armature.—The armature is the rotating part of the motor; it is composed of the spider, the core, the commutator, the winding and the shaft. The spider, shown by Fig. 108, is made up of the main casting, M, complete with rear core casting, R, and fan, F, and the front coil support casting, O, Fig. 109. The casting, M, is bored out to very accurate dimensions so that the armature shaft, S, will press in at 40 or more tons pressure. The outside dimension is also carefully finished, as the core is built upon this diameter, and a very close fit is desired. After boring and turning the casting, M, to proper

diameter, two keyways are cut to prevent turning of the core and commutator, respectively.

The core, C, is now built; it consists of iron punchings, a few mils thick, assembled on the casting, M, as shown in Fig. 109. The keyway and key serve also to line up these punchings or laminations so that the slots, T, will be properly formed. After the proper amount of laminations are put in the spider, they

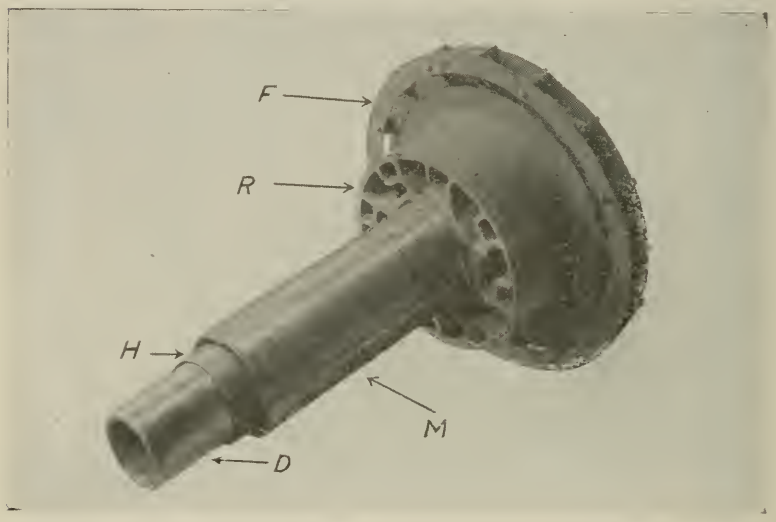


Fig. 108—An Armature Spider.

are put under a pressure of several tons, the front coil support, O, put into place, and the ring nut which holds all in place and under pressure, is screwed on the threads, H.

In present railway practice ventilated motors are used so that the maximum possible work can be gotten out of the locomotive. The passage of electric current through the windings of the armature results in heat; the amount of heat dissipated, depends on the ventilation of the motor, so that the more air is passed through, the harder the motor can be worked. A great many of the locomotives have the motors cooled by air furnished from an independent blower. In order to aid the passage of air through the motor, it is constructed with a fan on the rear end and ventilating ducts through the core and commutator. This same construction is used without external ventilation and a large increase in power is ob-

tained due to the larger amount of air which can be drawn through the motor thus getting rid of the heat.

A double fan is used and while one part is drawing the air through the ducts in the commutator and punchings, the other part of the fan is drawing air over the outside surface of the armature and through the field coils.

The Commutator.—The next step in the construction of the armature is to press the commutator, K, on the spider at diameter D, Fig. 108. The commutator is one of the most important parts of an electric motor; it serves as a means of

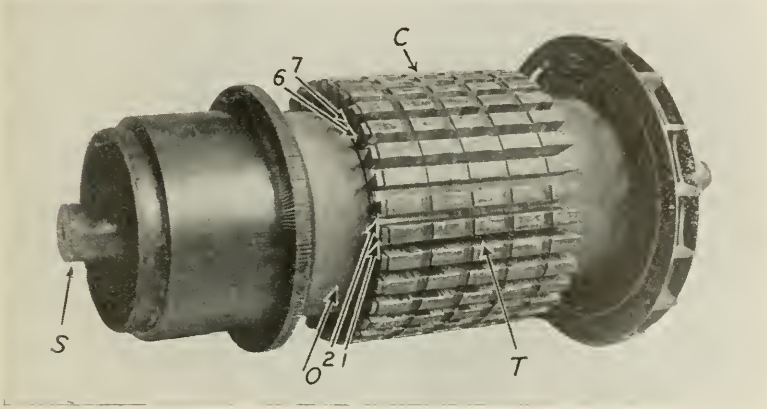


Fig. 109—An Armature Assembled and Ready for Winding.

connection between the winding or coils on the armature core and the source of power. All of the current taken by the motor flows in and out of the commutator through the brushes. The commutator also rotates with the spider and therefore the material of which it is composed must be a good heat-conducting metal and of high elastic limit. The best material for this use is hard drawn copper, and is invariably used.

An assembled commutator ready to press on the armature spider is shown in Fig. 110. A sectional drawing of the commutator and the details of the commutator parts, are shown in Figs. 111 and 112.

The commutator is made up of a certain number of bars R, the number depending on the number of slots T in the core

—Fig. 109— and the number of coils—Fig. 114—placed in these slots. Each bar is practically the same shape, as shown same general shape as the bar. The correct number of bars are assembled, and are then held together by a large iron ring in the cross sections. Each is insulated from the one on either side by a mica segment E, a few mils thick and of the

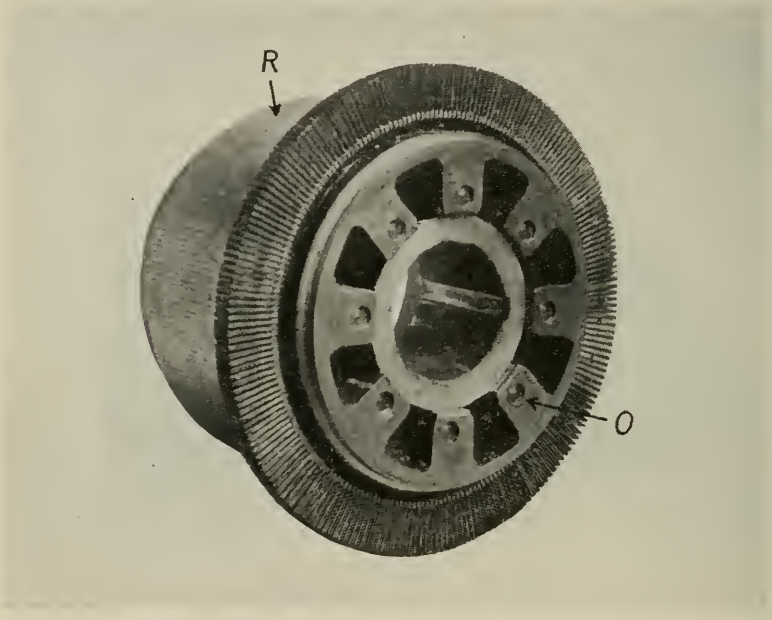


Fig. 110—An Assembled Commutator, Ready for Mounting.

which can be decreased in size, thus forcing the bars together under pressure. After assembling the commutator parts—as explained later—it is then necessary to place them in an oven heated to a temperature of approximately 140° C, so as to allow the mica to soften and conform to the irregularities of the copper, and thus prevent movement of bars after the commutator is finished. While at this temperature the commutator is placed under several tons pressure and the commutator segments securely held in this position.

Reference to Figs. 111 and 112 will show how the commutator segments are clamped and held. After the segments have been assembled the V-shaped slots are trued up in a

lathe, with the angles carefully secured. The segments are assembled on the metal bushing, A, with a mica V-ring, C, used as insulation. A mica bushing or sleeve, B, is slipped on around the bushing, A. Another mica V-ring, G, with a metal V-ring is used at the front end and the whole is clamped and held together either by bolts, O, Fig. 110, which pass through the

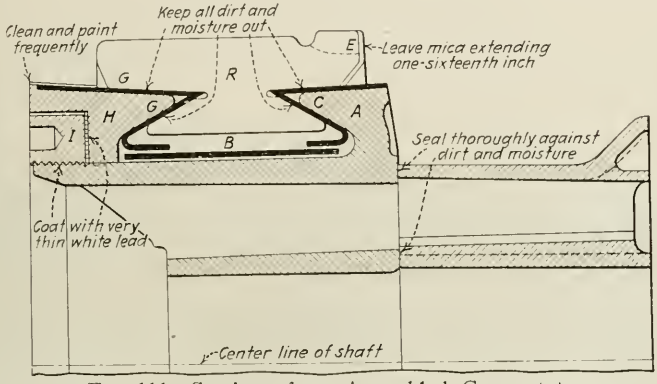


Fig. 111—Section of an Assembled Commutator.

front V-ring and screw into the rear one, or by a ring nut, I, Fig. 111, which tightens up on bushing, A. The front mica V-ring must be protected where it projects beyond the com-

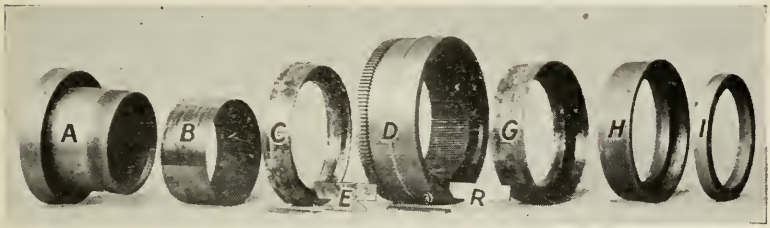


Fig. 112—Component Parts of a Commutator for a Railway Motor.

mutator bars; a banding of tape painted with insulating varnish is used for this purpose. A cross section of the complete armature is shown in Fig. 113.

The Armature Winding.—After the commutator has been pressed on the spider and the armature shaft pressed into place, the assembled parts are hung in a lathe ready for the armature winding.

The winding consists of coils of copper strap which have

been previously wound on a form so that the size and shape will be such that the coil will slip into the slots in the armature core without much forcing, thus preventing damage being done to the insulation. An armature coil is shown by Fig. 114. This coil is known as a "two-turn" strap-wound coil and each turn is made up of five separate copper straps or conductors which are insulated from each other usually by a flexible mica tape, the whole five being covered by tape, and

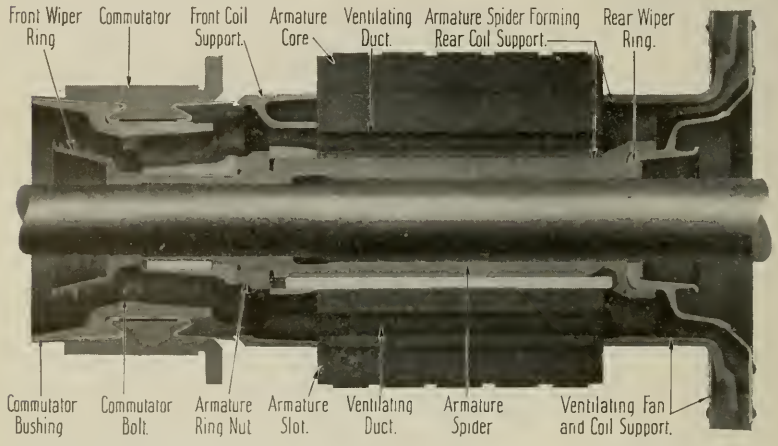


Fig. 113—Cross-Section of Complete Armature Shaft, Showing Assembly of Parts.

the two turns afterwards held securely together by more tape. After taping, the coil is placed in a vacuum-oven where it is heated and impregnated with an insulating varnish or compound which penetrates through the tape and fills all spaces, thus preventing moisture from entering and damaging the coil, and serving also as a good insulation. This compound or varnish hardens after the coil is removed from the oven.

Armature coils for small sized motors are also wound of insulated copper wire, but the strap-wound coils have many advantages. About ten per cent more copper can be placed in the same slot than can be used with wire-wound coils, which means that more current can flow through the coils, and hence more horsepower from the motor. This increase of copper is due to the fact that rectangular shaped wire adjusts itself to the rectangular shape of the slot and therefore no

space is lost. The heat generated by the flow of current through the copper wire can thus radiate to the core more easily and moreover, less compound or insulating varnish is required to fill spaces. This compound is not a good conductor of heat, so that with wire-wound coils where a considerable volume of compound would exist the heat would not be

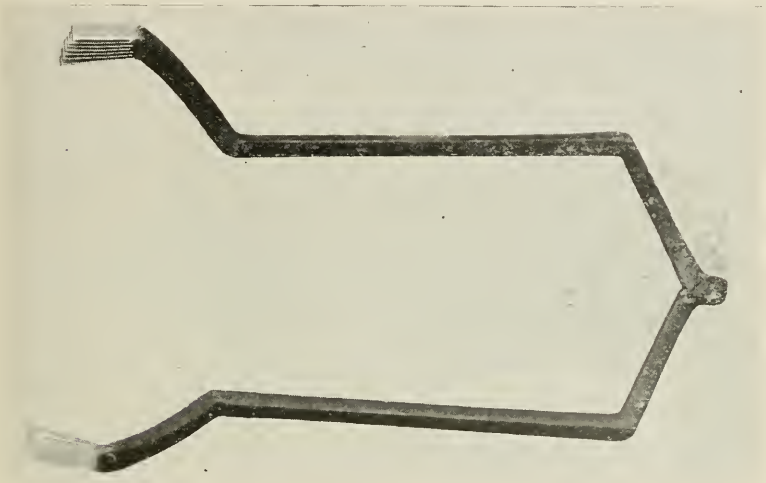


Fig. 114—A Two-Turn Strap-Wound Armature Coil.

conducted away as readily and the temperature of the motor windings would be higher.

The strap-wound coil also facilitates the winding of the armature and damage to the coils is less likely to occur, as the surfaces in contact with each other are flat surfaces and the pressure is distributed over a greater area than with the wire coils. In the latter the wires tend to cut the insulation as there is only line contact. In winding the armature it is sometimes necessary to pound the coil into place; in such an event the advantage of the strap coil is apparent.

Before placing the coils in the slots the rear-end bell and the front core castings are covered with tape and strips of treated cloth in order to protect the coils. Reference to Fig. 114 shows that the coil does not lie in two adjacent slots but that there are three or four slots between the two sides.

The core slots—see 1, 2, 6, and 7 on Fig. 109— are deep

enough to take two coils. Commencing with the first coil, which may be designated as coil, A, one side is placed at the bottom of slot 1, and the other side perhaps in the top half of slot No. 6; coil B, in bottom of slot 2 and top of 7. This proceedure is continued around the entire circumference of the armature After the last coil is put in place and the armature is completely wound each slot contains 20 conductors.

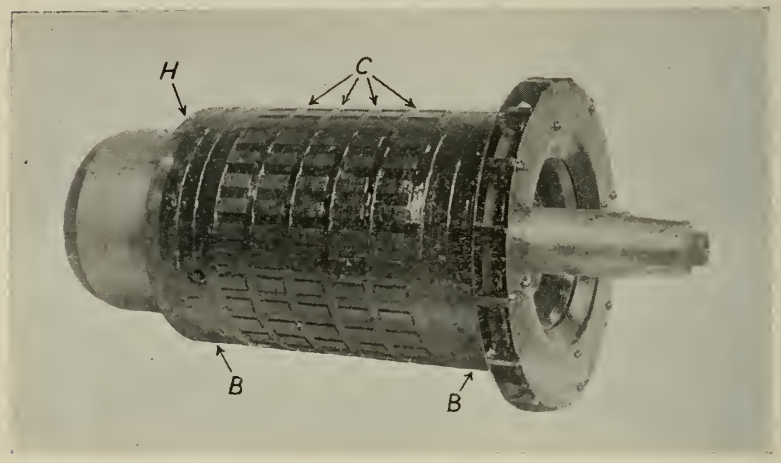


Fig. 115—Armature Complete, Ready for Mounting in the Frame of the Motor.

Each conductor is now placed in the saw cuts in the commutator bars and the armature is ready for banding.

Armature Banding.—The banding of an armature consists in placing steel wires around the core and over the coils so that they will not fly out of the slots due to the centrifugal force developed by the rotation of the armature. Fig. 115 shows an armature complete and ready to be placed in the motor housing. To protect the coils, and to keep dust from the windings, asbestos cloth hoods, H, are placed over the coils on the commutator and pinion ends; these hoods are held in place outside of the core slots. These bands are put on under several pounds pressure. Narrow bands known as "core bands" are placed at intervals along the core.

At intervals of a few inches, strips of tin are placed under the steel wires with the ends bent over to keep the wires to-

gether. To maintain the tension and to add mechanical strength, the band is soldered along its whole length. To give proper contact for the passage of the electric current the conductors placed in the saw cuts in the commutator bars are also soldered.

The Brush Holder.—One of the most important parts of the railway motor is the brush holder shown in Fig. 116. As the name implies this part of the motor carries the brushes, T, which are in contact with the commutator and through which

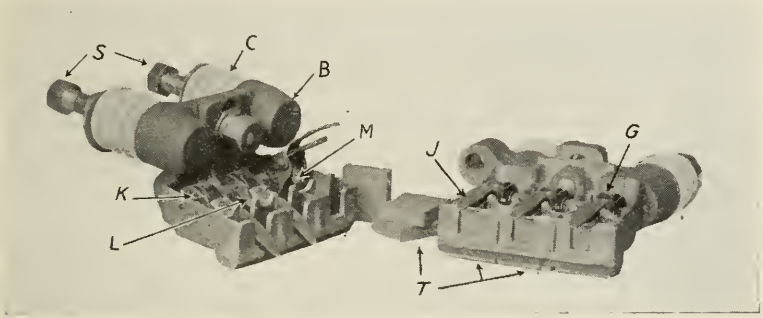


Fig. 116—Brush Holder for a Railway Motor.

the current flows into and out of the armature coils. The brushes are blocks of carbon which fit the holder, A, snugly but not tightly as one of the requirements of motor specifications is that these brushes must be constructed so that they can move vertically but that they shall not be loose in the holder.

The brush plays a very important part and can cause much trouble and damage to the motor; excessive wear of the commutator, sparking, etc., may be caused by the use of an improperly designed or improperly adjusted brush. As stated the brushes are made of carbon but there are numerous grades; hard and soft, with different processes of manufacture; and different motors operating under different conditions will require different grades of brushes in order to obtain the best operation.

These brush holders must be exactly located so as to bring the brushes to exactly the neutral points where no sparking exists; to insure this, the clamps holding the brush holders

are located by template. At the same time these holders must be insulated from the clamps and this is done as follows: Referring to Fig. 116: each boss, B, is drilled out and a piece of steel which has been drilled and tapped suitably to receive the bolt, S, is surrounded by insulation, either mica or micarta, and pressed into the boss. The corrugated insulators, C, are used to increase the creepage distance from the holder, which has the full voltage, to the bolts which is "ground." With this method of clamping, the entire holder can be moved up and down and proper clearance obtained between the commutator and the brush holder.

To obtain proper contact between the brushes and the commutator it is necessary to maintain a pressure on the brushes. This is accomplished by the spiral spring, G, which transmits its power to the brush through the hammer J. Different pressures are required for different conditions and the spring tension can be adjusted by the ratchet, K, and pawl, L. To prevent heating of the spring, and thus loss of tension, a copper braid, called a shunt, M, is provided, which conducts or "shunts" the current around the spring; one end of this shunt is riveted to the hammer and the other to the main holder. The wire which carries the current to the holder is held in the hole, O, by the screws, P. Two of these brush holders are used for all railway motors except those of large sizes, in which case a brush holder for each main field-pole is used. These holders are placed where they are easy to inspect and where the brushes can be replaced easily.

CHAPTER XXIII

MECHANICAL DESIGN OF THE ELECTRIC LOCOMOTIVE

The mechanical design of the electric locomotive differs materially from that of the steam locomotive which in general is fixed in relation to the fact that a boiler, firebox and cylinders must be carried on the locomotive frame. Crossheads are necessary and side rods and connecting rods must be used to change the reciprocating motion to rotation. The space between the drivers is limited so that the large mass must be carried mostly above the drivers, resulting in a relatively high center of gravity. There is little, if any, flexibility to this mass so the driving wheels are not rigidly secured to the frame but are loosely connected to it by means of journal boxes, pedestals, and spring rigging.

There are many advantages in steam locomotive design which have been recognized by electrical designers and incorporated in the mechanical design of electric locomotives.

On the first consideration it would appear as if the electric locomotive, with the elimination of reciprocating parts, would have riding qualities far superior to those of the steam locomotive. But this is not necessarily true; the electric locomotive must be proportioned correctly otherwise the riding qualities will not be of the best. Many factors enter into the design; the length of wheel base; type of leading and trailing truck; location of center pins; the location of the center of gravity of the mass in reference to the center pin and the height of the center of gravity above the rails. High speed steam locomotives operate only in one direction whereas the electric locomotive runs in either direction at full speed.

Consideration must be given not only to the mechanical design in order to obtain good tracking qualities, weight equalization and distribution, but also the very important

problems of the mechanical and electrical design of the motors themselves and of the transmission of power from the motors to the drivers. Each problem is dependent on the others; the size, weight and location of the motors in respect to the drivers, will affect the tracking qualities; the location of the motors determines, largely, the type of drive. The location of the center of gravity is an important consideration for the electrical designer. With a high center of gravity, there is a tendency toward rotation and the transverse force on the track is then much less than if the center of gravity is low and a considerable mass has to be moved transversely. Another very important consideration is the dead or non-spring borne weight per axle; it consists of the wheels, axles and journal boxes; with certain forms of drives it may be increased as part of the motor weight is also on the axle.

When the locomotive is running, any irregularity in the track transmits a blow to the driver, the intensity of this blow varying directly with the speed. Disregarding the center of gravity for a moment, the dead weight plays a very important part. This is the weight that the irregularities on the track must move and the transverse force or blow will depend upon the mass to be moved. Heavy dead weight should be eliminated.

Electric Locomotive Transmissions.—The electric motor has rotating motion as do the driving wheels and it would therefore appear to be a very simple matter to transmit the power from the motor to the axles. However, the system of transmission is inseparable from the weight distribution and equalization, with the height of the center of gravity, and the dead weight, that the subject involves more than the mere coupling of the motors to the axles. Some idea of the problem is obtained when it is known that the weight of the electrical equipment exceeds the weight of the other parts of the locomotive. Some types of transmission may be satisfactory for a certain service under certain conditions and still be entirely inadequate for a different service or different conditions. These various factors make transmission one of the most intricate problems in electric locomotive design.

With no limiting determining factors, as a boiler or firebox, to affect electric locomotive design, there have been

developed many different arrangements of drives and mechanical construction. These can be classified under several headings: direct-geared drive; gearless drive; gear-and-quill drive; side rod drive and gear-and-side-rod drive.

Direct-Geared Drive:—The direct-geared drive shown in Fig. 117 is the common method used for driving electric cars in city streets and on interurban lines. The motor frame has bearings, A, which fit directly on the axle and the other side of the frame is fitted with a nose, B, which is supported on the truck. Gearing is used to connect the motor power to the driving axle, a gear, G, being pressed on the axle and a pinion,

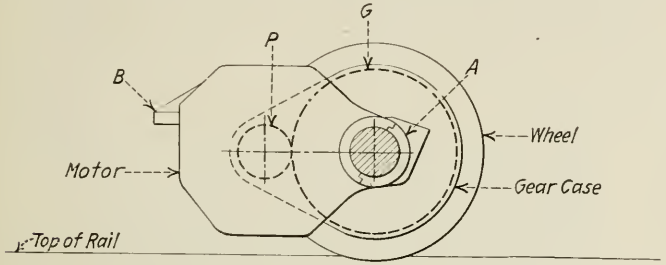


Fig. 117—Arrangement of Parts for Direct-Geared Drive.

P, mounted on the armature shaft which meshes with the gear. This arrangement has been used quite extensively on electric locomotives of the single type and those of medium size. For slow speed work with light or medium sized motors the arrangement has the advantage of low maintenance cost, but for heavy duty and high speed work the arrangement is not the best as in addition to the weight of the wheels and axle there is a large and excessive dead weight consisting of the gear and approximately five-eighths of the motor weight.

Gearless Drives.—At one time it seemed a logical proceedure to eliminate gearing. The direct-geared drive was not satisfactory for high speed work and gearless motor drives were designed. Two different arrangements have been used. The drive shown in Fig. 118 has the armature pressed on the driving axle and the fields, of which there are two, are carried on the truck frame. The arrangement is used on the New York Central locomotives and on the latest Chicago, Milwaukee & St. Paul locomotive built by the General Elec-

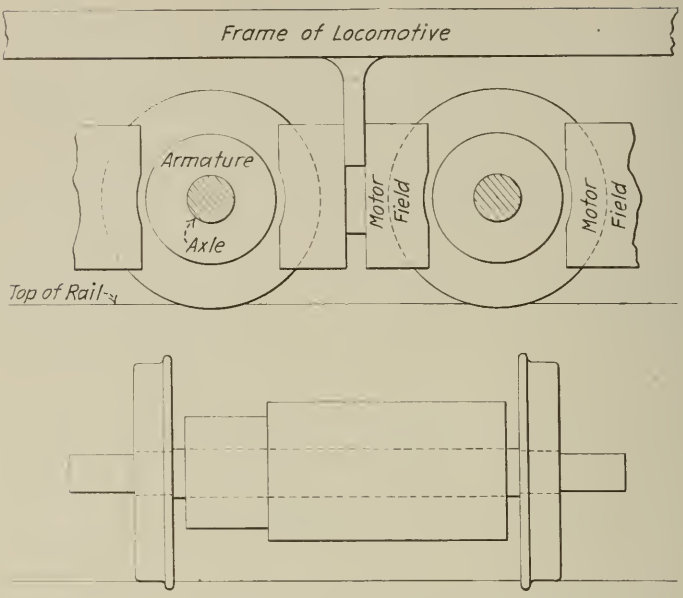


FIG. 118—Gearless Drive—Armature on the Axle.

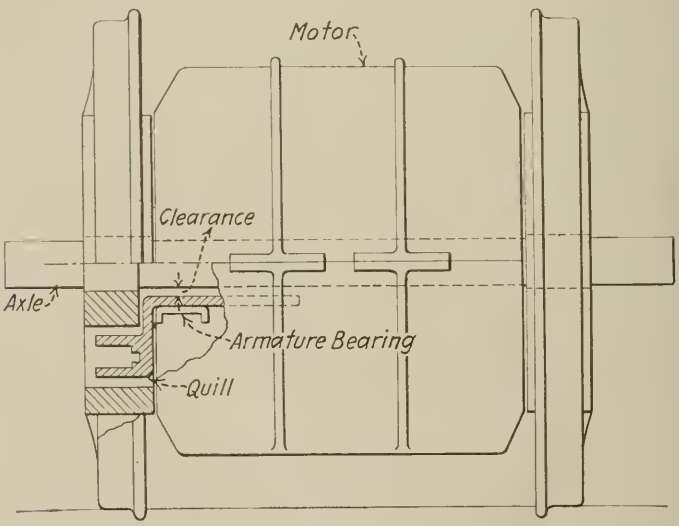


FIG. 119—Gearless Drive—Armature on a Quill.

tric Company. The other design, as shown in Fig. 119, has the armature carried on a quill surrounding the axle and drives the wheels through flexible spring connections. This arrangement is used on the original New Haven passenger locomotives built by the Westinghouse Company. The first arrangement has a dead weight of approximately 9,500 lb.

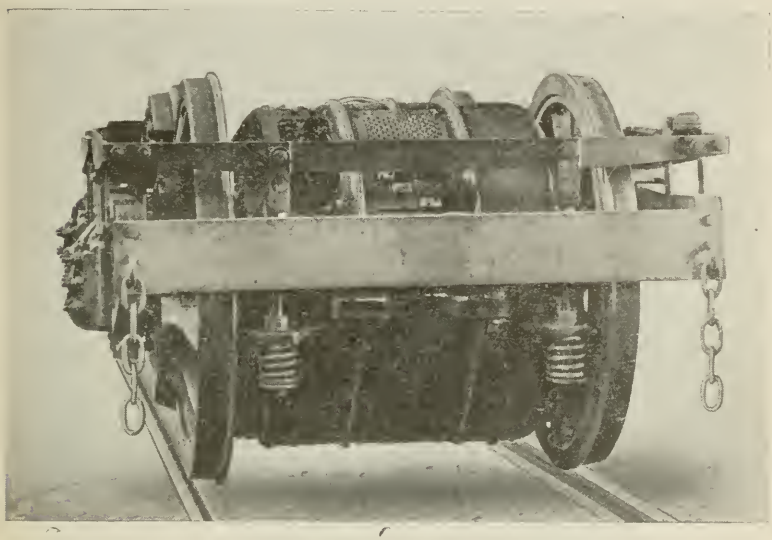


FIG. 120—View Showing Motor Mounted on the Truck and the Cradle from Which the Motor is Hung.

per axle, while with the other gearless drive the entire motor weight, including the quill, is suspended from a cradle supported at the journal boxes.

The use of a quill is not new. The armatures used on early locomotives built for use on the Baltimore & Ohio at Baltimore were fitted with quills but rubber pads were used to cushion the impact between the armature and the drivers.

Gear-and-Quill Drive.—While in many ways the gearless drive is ideal, the dead weight is not a minimum and moreover the center of gravity is low. Great improvement has been made in gearing so that today it is a reliable part of the locomotive equipment. It has advantages, as will be explained later, so that many new drives have been designed.

The gear-and-quill drive can be divided into two arrange-

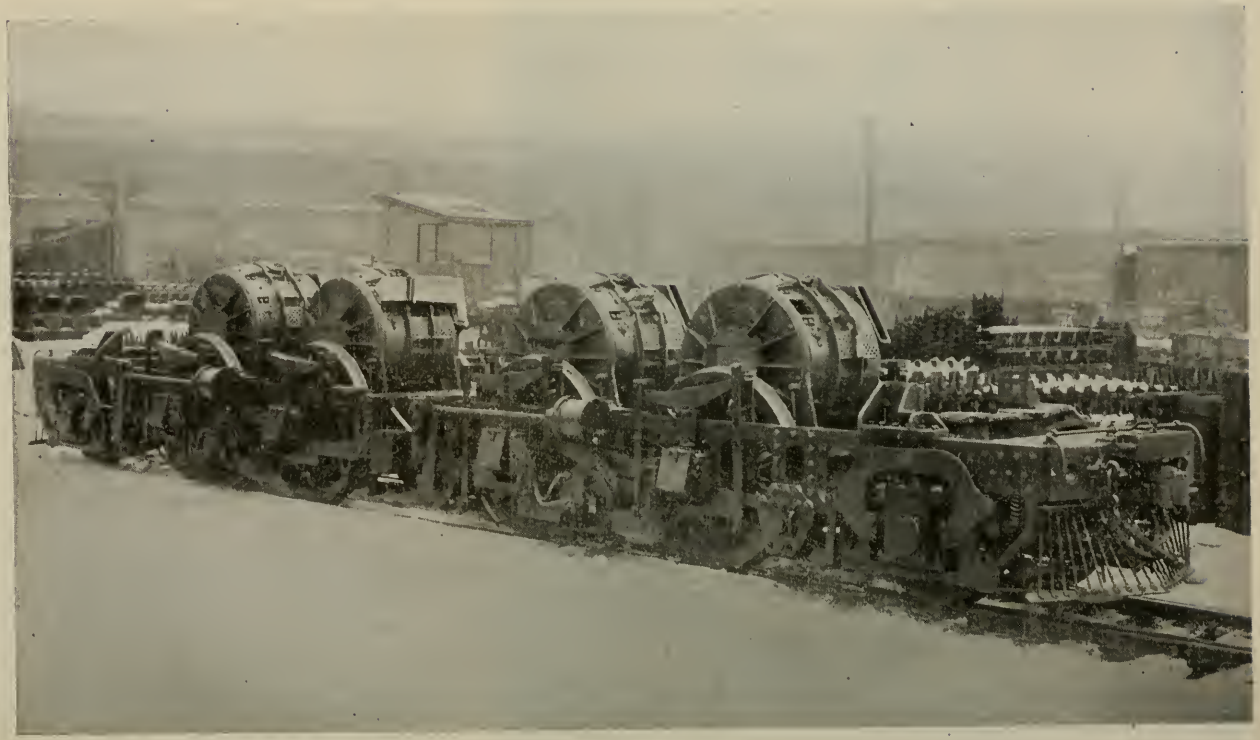


Fig. 121—View of Locomotive Chassis Which Has Single-Motor Gear-and-Quill Drive.

ments. The first consists of a single motor per driving axle; the second of two motors—called twin motors—mounted in one frame, per driving axle. The first arrangement is shown in Fig. 122. A hollow quill surrounds the axle, the inside bore being sufficiently large, compared with the axle diameter, to permit a considerable movement of the axle so that it can conform to the track irregularities without affecting the motor or bringing any of the motor weight on the axle as dead

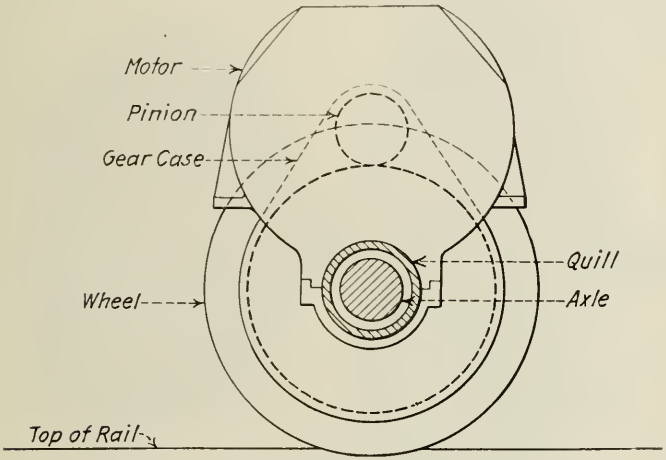


Fig. 122—Gear-and-Quill Drive Using Single Motor.

weight. The motor is bolted to the main frame of the locomotive. On the motor housing are two bearings which support the quill and in which the quill rotates as the drivers revolve; the quill is thus held concentric with the axle. At each end of the quill near the wheel is mounted a gear which meshes with a pinion fitted to each end of the armature shaft. Two gears are necessary for the one large armature as heavy duty is performed and the loads carried by the teeth must not exceed the safe limit. It is preferable to use flexible gears so that both pinions will be working and dividing the load. The flexible gear consists of a center which is pressed on the quill; around this center is the gear rim, not fitted rigidly but driving the center through the springs interposed to cushion the forces. A similar construction used

in connection with gears and side rods is shown in Fig. 130.

The driving from the quill to the drivers is accomplished by bolting castings to the gear center; these castings projecting between the spokes of the wheels. Coil springs are then inserted between the castings and as shown in Fig. 123. The torque of the motor is transmitted through these springs to the driver. The springs do not interfere with the vertical

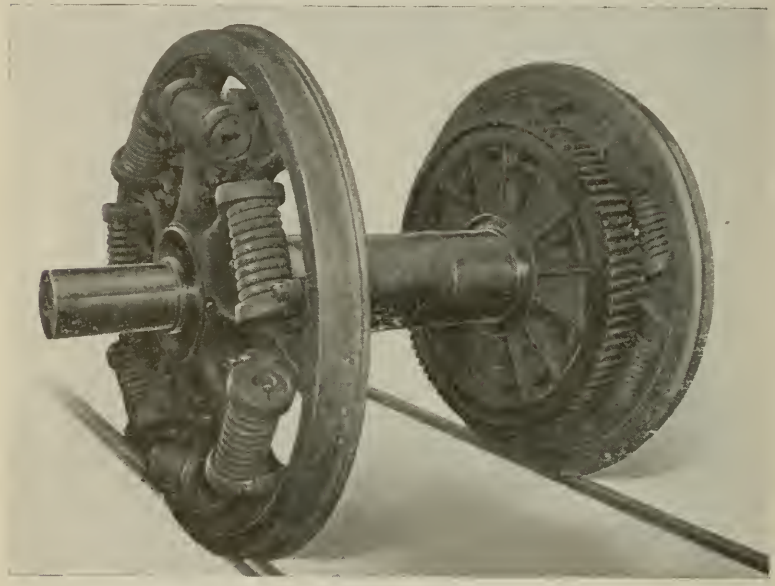


Fig. 123—Assembly of Quill Drive with Torque Springs in Place.

movement of the wheel, but form a cushioned drive. With this arrangement of motor mounting, the center of gravity is high; the motor, quill and gears are supported from the truck frame and are thus spring supported; and the dead weight is a minimum, consisting only of the wheels and axles.

The "twin motor" arrangement—Fig. 124—is practically the same as that of the single motor. One difference is the use of only one gear on the quill, only one being necessary as the same total armature torque is divided between two twin armatures, each one of which delivers one-half of the tractive effort. The pinion of each armature meshes with the single gear. The tooth pressure is reduced one-half so

that it is not even necessary to increase the width of the face of the gear. The elimination of one gear is an advantage as more space is available for the motor and a longer armature can be used, resulting in increased power. By dividing the power of one armature into the two "twin" armatures and taking advantage of the extra space, two small armatures which may be easily handled, take the place of one large,

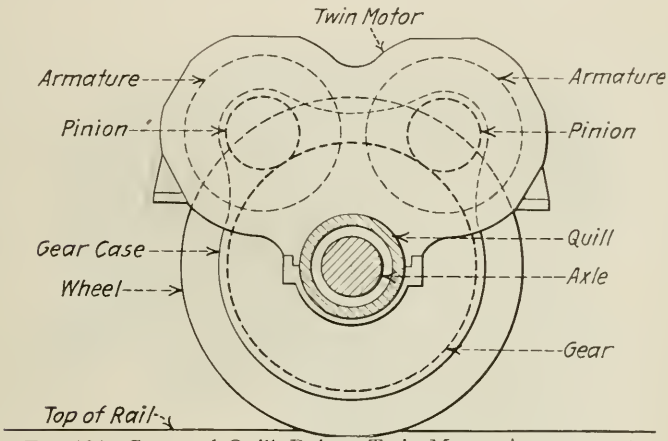


FIG. 124—Gear-and-Quill Drive—Twin-Motor Arrangement.

heavy armature; usually the complete "twin motor" weighs less than the single motor.

The use of gearing also permits a considerable saving in cost. Where a motor is geared directly to the driving axles the revolutions must be the same as the drivers and this means a comparatively low armature speed—slow speed motors mean additional weight and cost. The use of intermediate gearing allows higher speed and smaller motors to be used for the same horsepower output.

While it is possible to obtain a higher factor of adhesion between the rails and drivers with an electric locomotive than with a steam locomotive, due to the uniform torque of the electric motor, wheels do slip and stresses are imposed upon the mechanical transmission. The magnitude of these stresses depends on the stored energy of the motor due to rotation—the rotary moment of inertia. In the two drives just described the "twin motor" arrangement has a lesser

rotary moment of inertia than the single motor; the stresses are, therefore, much less and maintenance also costs less.

Side Rod Drive.—In the case of the drives already mentioned — direct-geared, gearless, and gear-and-quill — the capacity of the motor unit per driving axle is limited, due to the fact that it must occupy the space between the wheels. If the motor is removed from this space and mounted above

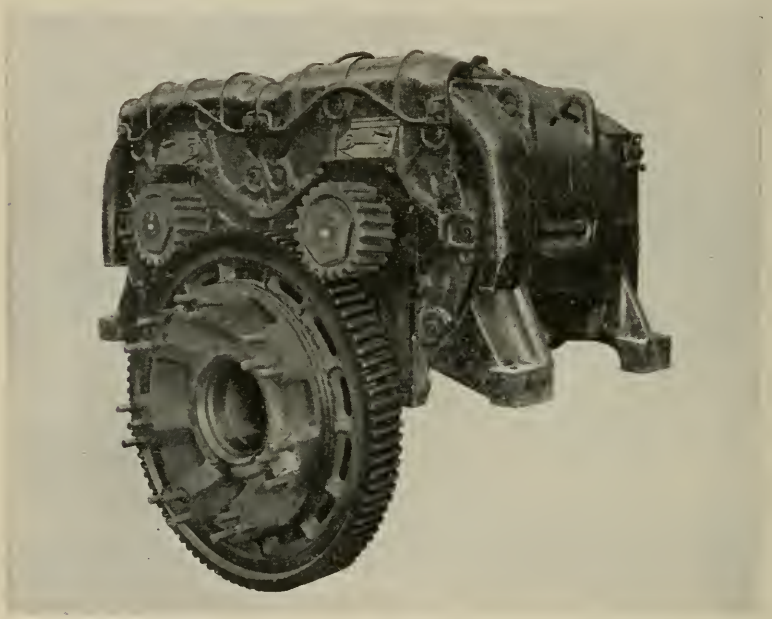


Fig. 125—Twin-Motor, Gear-and-Quill Drive, Showing Gear and Motors in Position.

the wheels the full width of the cab is available and it is then easily possible to design a motor having a capacity several times that which can be utilized on one pair of drivers and it becomes necessary to couple several pairs to the one motor. The very large motor, while expensive to construct, eliminates a large number of individual drives and generally the cost of the locomotive per unit horsepower is less.

A locomotive of such a design used in the P. R. R. Terminal Electrification at New York City is shown in Fig. 126. The large motor is mounted on the locomotive frame and is spring

supported. Power is transmitted to the drivers by connecting and side rods. Each end of the armature shaft is fitted with quartered cranks; rods connect these to cranks mounted on a jack shaft which is also carried on the frame and located level with the driving axles. High center of gravity is thus obtained and the dead weight is reduced to a minimum.

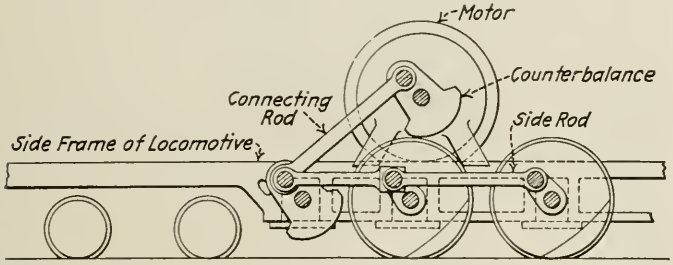


Fig. 126—Arrangement of Parts When Side-Rod Drive is Used.

By using side rods the frame and wheel arrangement of steam locomotive design can be practically duplicated, and the electric locomotive of this type has the advantage, over the corresponding steam locomotive, of there being no reciprocating motion, all parts of the drive rotating in a circle.

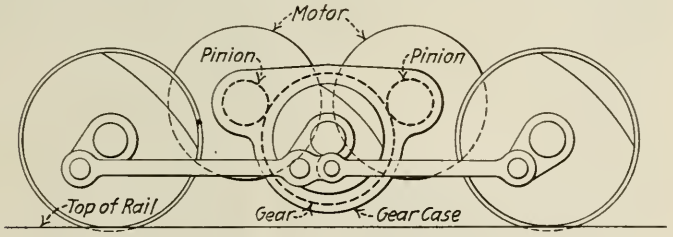


Fig. 127—Combined Gear and Side Rod Drive.

This condition tends to eliminate dynamic augment—in the case of the steam locomotive a condition due to the impossibility of securing exact counter-balancing and therefore as the locomotive moves along, imposing a vertical blow or stress on the track, additional to the weight on the drivers.

An electric locomotive with side rods has a certain advantage over one with independent drive for each axle, in that it

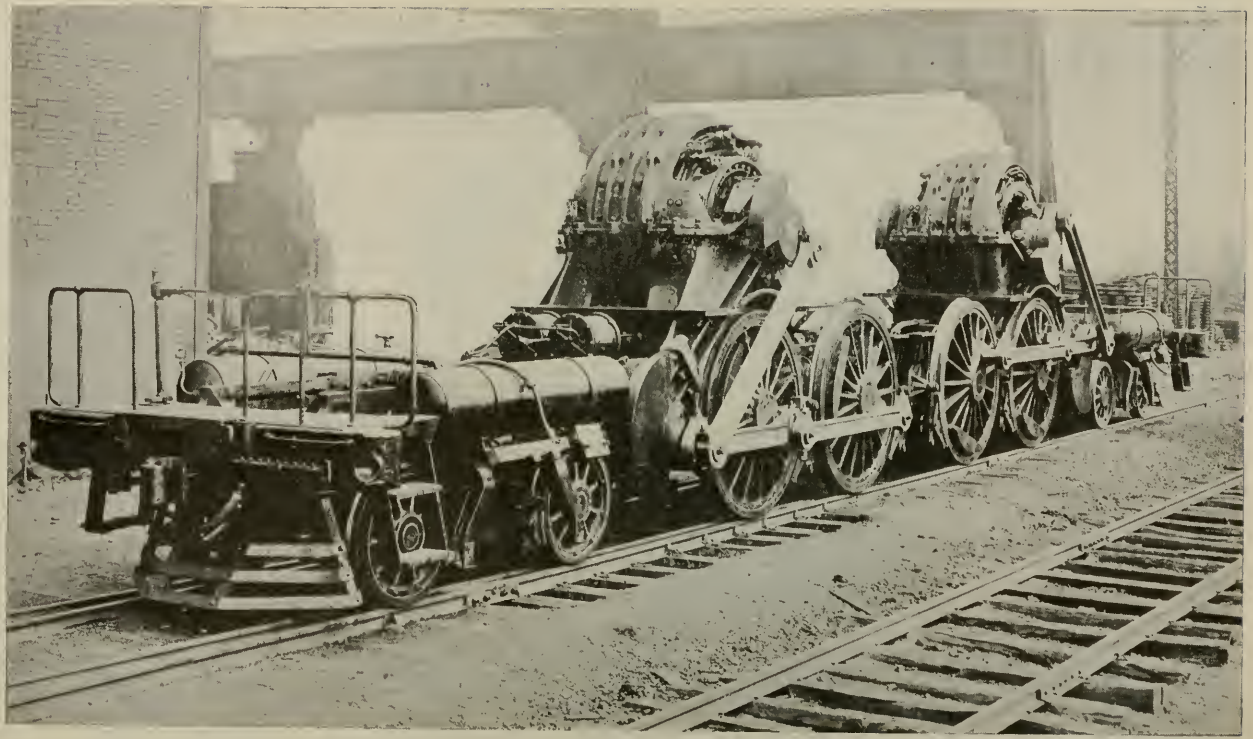


Fig. 128—Side-Rod Drive of Locomotive Used by Pennsylvania Railroad in New York Terminal Service.

is not affected by "weight transfer" which occurs when the locomotive is pulling a load and is greatest when the drawbar pull is the greatest at starting. The drawbar is located a few feet above the rail while the tractive effort is at the rim of the drivers at the rail so that a mechanical couple is formed. The pull at the drawbar causes some of the weight on the leading drivers to be transferred to the rear drivers—with

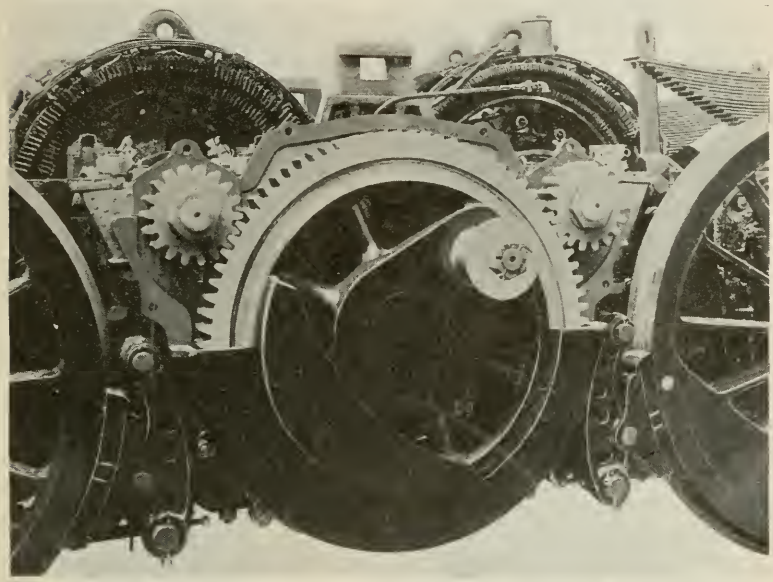


FIG. 129—Gear and Side Rod Drive as Used on the Norfolk & Western

short wheel bases this transfer may be as much as 10 per cent or even more; with good wheel distribution the weight transfer may be kept as low as 5 or 6 per cent.

With the independent axle drive the drawbar will be governed by the weight on the leading axle and use cannot be made of the weight transferred to the rear axles. As more and more power is fed into the motors the leading pair of wheels will slip first throwing the load on the others which in turn will also slip. Slippery tracks also may cause one pair of wheels to slip with the same results.

The side rod drive eliminates this difficulty; all drivers are coupled together and the weight transferred is not lost for

FIG. 130—Flexible Gear—Front and Rear View.

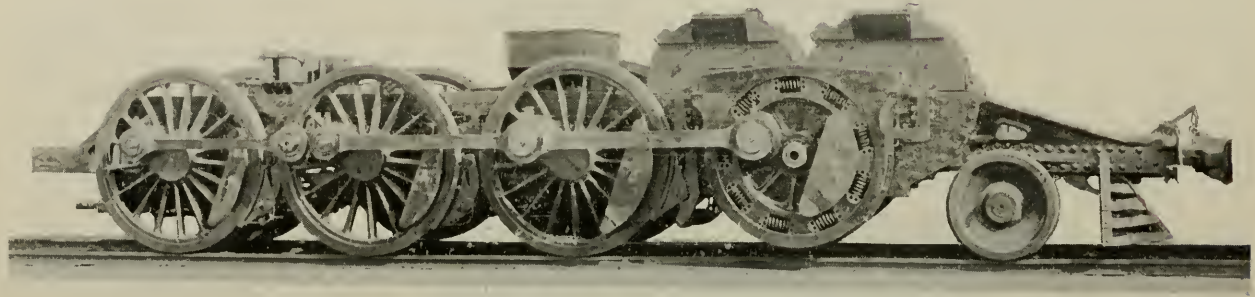
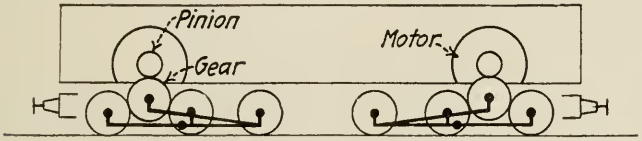


FIG. 131—Gear and Side Rod Drive as Used on the Pennsylvania Railroad Split-Phase Locomotives.

drawbar pull, as one pair of drivers cannot slip independently of the others.

Gear and Side Rod Drive.—In the case of the side rod drive, the electrical designer has ample space to properly proportion the motor, as regards armature diameter and armature length, to give maximum efficiency, but still cannot obtain the advantages gained by the use of gearing, when, as explained



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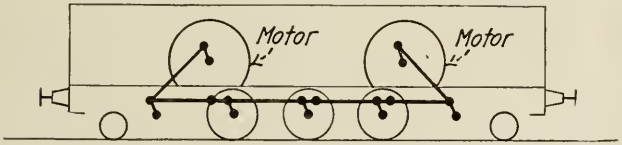
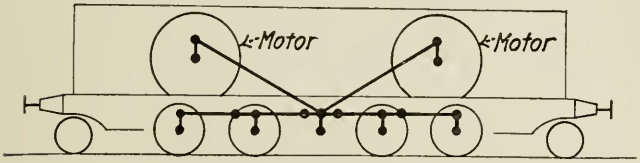
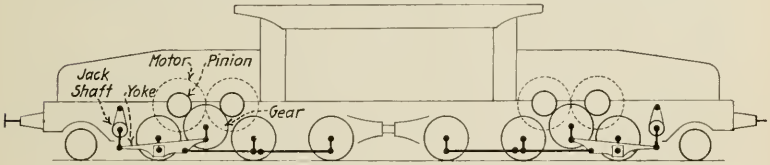


Built by A. E. G.—Chemin De Fer Du Midi—France



Built by Siemens—Prussian—Hessian State Railways—Germany



Built by Oerlikon Company—Swiss Federal Railways

FIG. 132—Examples of Side-Rod Drives Used on Foreign Locomotives.

in a previous paragraph, a relatively high speed motor can be used; the gear and side rod drive—Fig. 127—combines the advantages of both types. In this design the gear is located between and outside of the drivers so that a large space is available for the motor itself. The gear reduction makes it possible to have a high speed motor armature for a comparatively low speed locomotive. The side rods eliminate the effect of weight transfer and, while the center of gravity is not as high as in some other drives, the dead weight per axle is kept at a

minimum. The motor, gearing and jack shaft are all supported by the locomotive frame.

Wheel Arrangements and Frame Design.—The foregoing has referred to the types of drives without mention of the wheel arrangement or frame design. While the method of drive will affect wheel arrangement there are many variations obtainable for the same form of drive. Without going into great detail there are:

1st—The arrangement where all weight is on the drivers—sub-divided into two classes:

(a) Where all drivers are carried in a single rigid frame integral with the cab and thus forming a rigid wheel base.

(b) Where the drivers are contained in two trucks. The cab may be an integral part of the frame with the drawbar pull transmitted through the center pins on the truck; or the trucks may be articulated at the inner ends, and the cab, which is not subjected to any of the drawbar pull nor to the buffing stresses, is carried on top of the trucks in the usual way. In order that the locomotive may pass around curves, the center pins must be free to move within small limits. With this latter arrangement the truck centers are not subjected to the excessive stresses which would otherwise exist in heavy service.

2nd—The arrangement where a bogie or pony truck is used to guide the drivers. These idle wheels have been applied to each of the above arrangements and make it possible for the locomotive to have better riding qualities and operate at higher speeds without undue cost for track maintenance.

Drives on Foreign Locomotives.—There has been a great deal of thought and study given to the electric locomotive by the various foreign Governments and manufacturers. Nearly every locomotive has a drive embodying the use of the side rod. The arrangements in several cases—see Fig. 132—are extremely interesting. Some valuable data in tabular form is given in the appendix to this volume, on pages 323 to 327.

CHAPTER XXIV

INSPECTION AND MAINTENANCE

The inspection and maintenance of the electric locomotive is radically different from that of the steam locomotive, with a few exceptions. The electric locomotive has many of its mechanical parts, especially the running gear, patterned after steam locomotive designs so that the inspection and maintenance of the side rods—if any—the grease cups, the driving boxes, wedges, guiding or trailing trucks, tires, wheels, draft rigging, air brake, etc., is the same as for the steam locomotive. The boiler, air pump, throttle and cylinders of the steam locomotive are replaced on the locomotive by the electrical apparatus—the motor driven air compressor, the master controller and main driving motors; the difference lies in the inspection and maintenance of the electrical parts.

The advantages of inspection and maintenance place the electric locomotive in a favorable position; the steam locomotive, after comparatively few miles run, must go to the round house to have the fire cleaned, etc., and, of course, during this time is not available for service. The electric locomotive, on the other hand, not being a self-contained power unit but receiving its power from a central power source, has the great advantage that it can run hour after hour and be available for service at all times day after day with only a lay over for shop inspection of three or four hours every two thousand to three thousand miles run. With the present designs of the electrical apparatus the inspection can be made on a mileage basis and it is not even necessary to oil the motor bearings between inspections. Many electric locomotives are making more than 10,000 miles per month and some, 400 miles per day for 28 consecutive days.

The inspection and maintenance can be divided under three headings, viz: light inspection by the shop force after every

3000 miles run—requiring only a few hours; heavy inspection and overhauling after every 100,000 miles—requiring several days; and inspection by the engineer prior to taking the locomotive out on a run—requiring only a few minutes.

Light Inspection.—Light inspection consists of going over all the electrical parts of the locomotive to see that they are in proper adjustment, the terminals tight, parts cleaned of grit and dust and properly lubricated. Generally this work is divided among several men. One man will inspect the running gear and draft rigging for loose or broken bolts, etc., worn brasses and sharp flanges. Another man will inspect third-rail shoes, shoe beams, fuse boxes and pantagraphs—if locomotive is equipped with this device—oiling or greasing the movable parts and replacing broken or weak springs. The third-rail shoes are gauged for proper height in respect to the top of the running rails,—everything must be in proper condition. The pantagraphs should be absolutely free to move and must not bind due to any of the bearings getting out of line. The upward pressure should be checked with a spring balance which will determine whether there is sufficient pressure to keep the pantagraph shoe in contact with the wire when moving at high speed; the shoes should be changed if worn badly.

Inside the locomotive other men are checking the air brakes for proper reservoir and train line pressures and for free operation of the valves, etc.; auxiliary apparatus—the compressors and blowers, the lights, the governors, the resistance, the fuses and other auxiliary apparatus which may be installed are also inspected.

The only parts now left for the inspection are the control apparatus and the main motors; inspection of these parts is important and only experienced men should do this work. There are a large number of control circuits connecting the master controllers with the various pieces of apparatus; these circuits must be kept intact. The master controller covers are removed, the fingers inspected for wear and for proper contact with the controller drum; loose terminals are tightened and finally, before closing up the covers, the drum is wiped with a thin layer of oil so as to prevent undue wear or "cutting" of the fingers which would result if the drum

was left dry. This same method of inspection is followed on other pieces of apparatus. In connection with the switch groups all control wiring is checked at the magnet valves to detect loose connections. The main contacts are examined, and cleaned if necessary, and worn contacts and burned arcing horns are replaced if required.

Cleanliness is important and cheese cloth should be used to wipe off all parts to keep them free from oil and dust. Main contacts may be located on revolving drums and must be lubricated to prevent cutting; a slight film of oil applied to the main contractors will increase their life.

It is important that all main connections be kept tight, otherwise the large amounts of current handled by the locomotive will overheat them.

The inspection of the motor consists in a careful checking of the brushes, maintaining proper pressure on them and replacing short or broken ones, keeping the band at the commutator and insulators clean, gauging the air gap for clearance, inspecting gears and pinions, and lubricating motor bearings by filling the housing oil compartment to the proper depth of oil.

Heavy Inspection.—Economy of operation and reliability of service demand that, periodically, the locomotive should be thoroughly overhauled. The length of time between these overhauling periods, representing mileage, depends a great deal on the service required of the locomotives and the service performed, and whether the locomotive is working at all times up to full capacity.

At the heavy inspection periods the apparatus is removed from the locomotive, taken apart and thoroughly repaired before replacing. After a general overhaul a locomotive is, for all practical purposes, as good as new.

Engineer's Inspection.—Every engineer about to start on a run, should know for his own satisfaction, that the locomotive is in good running condition and there is a certain inspection that he should make although the locomotive may come directly from the light or heavy inspection shop.

In addition to the looking over and oiling of wedges, side rods, etc., he should note that the air compressor is pumping to proper pressure as regulated by the governor; that the

storage battery used by the control circuits is sufficiently charged, testing it by means of a test light available for this use; that the auxiliary apparatus such as sanders, lights, and automatic bell-ringer, are in proper condition; that the pantagraphs raise and lower properly—also the third-rail shoes, if used on the same locomotive; that the blowers which supply air for cooling the motors and transformers—if used—operate properly; that the main switches operate in the correct order when the master controller is notched up.

Each type of locomotive is different and naturally there are special instructions as regards inspection and maintenance for each type. In general, it is essential that every one whose duties are in any way connected with the operation or maintenance of electric locomotives, should have as complete a knowledge as possible of the electrical apparatus. The engineer should familiarize himself with the name, location and purpose of each item of apparatus which goes to make up the whole. He should know, also, the general principles upon which the apparatus functions, how to operate it and what procedure to follow in case of failure.

CHAPTER XXV

THE SPEED-TIME CURVE

The power required to start and haul a train is expressed in terms of tractive effort at the rims of the driving wheels. This tractive effort is used in overcoming certain factors, namely: train resistance, acceleration, grade resistance, and curve resistance.

For train resistance, in the following problem, use the curves shown by Fig. 30.

Acceleration is the rate of change in velocity. A value will be taken of 100 lb. tractive effort required per ton to obtain an acceleration rate of one mile per hour per second. For other rates of acceleration the value will be proportional.

The grade resistance is the tractive effort necessary to

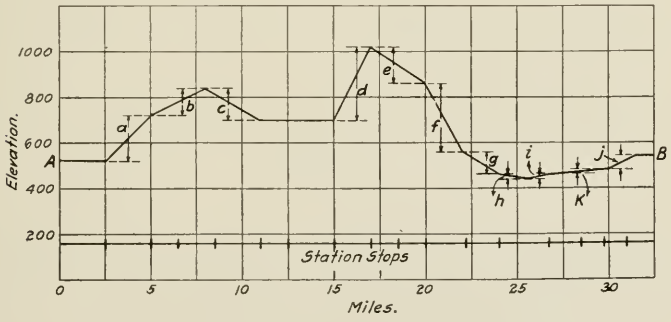


Fig. 133—Profile of a Railway, Shown Graphically.

overcome the lifting of the car through the vertical distance, and for a 1 per cent grade is 1 per cent of a ton, or 20 lb. per ton. This resistance is directly proportional to the grade; for instance, for 2 per cent grade it is 40 lb. per ton, etc. The

curve resistance at best is roughly approximate; a value of 0.8 lb. per ton is generally used.

Problem.—The problem which will be worked out is based upon the following assumptions:

Profile.—The profile of the line over which the electrical equipment is to operate is shown by Fig. 133.

Length of Line.—32.5 miles.

Number of Station Stops.—16 intermediate.

Running Time.—1 hour, 8 minutes.

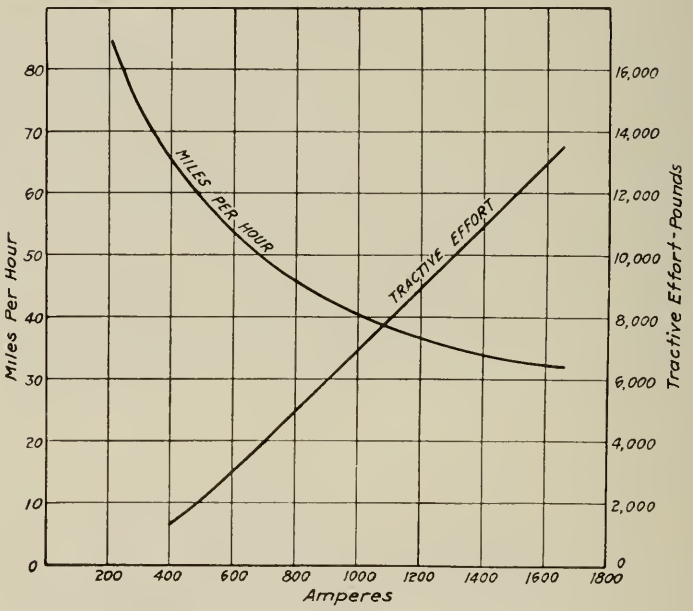


Fig. 134—Characteristic Curves of a Railway Motor.

Make-up of Train.—The train is to consist of an electric locomotive and eight cars, each car weighing 60 tons without load. Average passenger load is to be taken as 60 passengers per car.

Length of stop.—Average length of station stops, 40 seconds.

Locomotive.—The weight of the locomotive is 120 tons. It is equipped with 4 motors for operation on 600 volts direct current, characteristic curves of same shown by Fig. 134. This set of curves is for one motor only, but has been drawn for the correct gear ratio and wheel diameter of this locomo-

tive. The control in the locomotive is so arranged that the four motors are first connected in series; then in series-parallel and finally in full parallel. The motor combinations are shown by Fig. 25.

Typical Run.—The train operating over this line, starting from point A, Fig. 133, and making all station stops, will accelerate and stop 17 times. There are therefore 17 cycles of operation. Very close results can be obtained for the whole run by getting the performance for the average of these 17 cycles. In electric traction terms, this average is called the "Typical Run" and is determined as follows: The average distance for the typical run will be:

$$\frac{32.5 \text{ (miles)} \times 5{,}280 \text{ (ft.)}}{17} = 10{,}094 \text{ ft.}$$

or for convenience, 10,100 ft.

The average time over this average distance will be:

$$\frac{60 \times 68 \text{ (min.)}}{17} = 240 \text{ seconds.}$$

Equivalent Grade.—A glance at the profile shows that the two terminals of the line are at nearly the same elevation so that the train operating from A to B, after completing its run, has practically no potential energy at B, over what it had at A. However, operating over a rolling profile with terminals at the same elevation requires more energy than operating over a level line, as not all of the energy expended in lifting, up the grades, can be used on the down grades. A regenerative system would conserve some of this energy, but that system is not considered in this case.

To determine the approximate energy consumption for operating the train over a rolling profile, we must assume a certain constant resistance in addition to the train resistance. This is best accomplished by assuming that the train is operating against a grade. This assumption of grade is known as the "equivalent grade" and is determined by the formula—

$$\text{Equivalent grade (per cent)} = \frac{100 \times S}{2 \times L}$$

where S = the sum (in feet) of the rise in both directions
L = the length (in feet) of the round trip.

Referring to Fig. 133, the equivalent grade for our problem then is:

$$\frac{(a+b+c+d+e+f+g+h+i+j+k) \times 100}{2 \times 65 \times 5{,}280} =$$

$$\frac{(200+120+140+320+160+300+100+20+20+20+60) \times 100}{686{,}400}$$

$$= \frac{146{,}000}{686{,}400} = 0.213 \text{ per cent.}$$

The Speed-Time Curve.—Having determined the typical run—a distance of 10,000 ft., the train to consume 240 seconds over this distance, including the stop of 40 seconds, and operating against the equivalent grade of 0.213 per cent—plot the speed-time curve of the train over this typical run.

The total train weight is:

8 cars at 60 tons each	480	tons
Total number of passengers (60 × 8) = 480 at 140 lb. each =	33.6	tons
Weight of locomotive	120	tons
Total	633.6	tons

Acceleration for steam passenger trains is from 0.2 to 0.5 miles per hour per second, while in the case of electric locomotives, acceleration will vary from 0.3 to 1 m.p.h.p.s. Let us assume an acceleration in this case of 0.7 m.p.h.p.s.

The tractive effort required for acceleration will then be $0.7 \times 100 \times 633.6 = 44{,}352$ lb.

The train resistance at moment of starting is high but drops off very rapidly at a speed of 1 to 2 miles per hour and then increases slightly with increased speed. It is possible to take into account this varying train resistance, but for all prac-

tical purposes a straight line acceleration, from zero speed up to the speed at which the motor curve is reached, is satisfactory.

The speed at which the motor curve is reached and which is the end of the straight line acceleration, is found by trial Let us assume that this straight line acceleration will stop at 25 m.p.h. Referring to Fig. 30 of the train resistance curves, the train resistance for a train weight of 633.6 tons running at 25 m.p.h. is 5,500 lb. Since the equivalent grade is 0.213 per cent this additional resistance must be taken into account. To operate over a 0.213 per cent grade requires 0.213 $\times$ 20 lb. or 4.26 lb. per ton. For the weight of train under consideration the total grade resistance is 633.6 $\times$ 4.26 = 2,700 lb. The total tractive effort then to overcome the train resistance and grade resistance and to accelerate this train at 0.7 m.h.p.s., assuming that straight line acceleration stopped at 25 m.p.h., would be 44,352 + 5,500 + 2,700 = 52,552 lb. This is the total tractive effort required of the locomotive and, since it is equipped with four motors, a tractive effort of 13,140 lb. per motor is required. Referring to the motor curve, Fig. 134, we find that the speed corresponding to the tractive effort of 13,140 lb. is 32.5 m.p.h. This shows at once that the assumption of 25 m.p.h. was too low and that it should probably be a little lower than 32.5 m.p.h. As a second trial, we will assume that the straight line acceleration stops at 32.m.p.h. The train resistance as taken from Fig. 30 is then 6,220 lb. The total tractive effort required is 44,352 + 6,220 + 2,700=53,272 lb. or 13,320 lb. per motor. The speed corresponding to this tractive effort is 32 m.p.h., which is therefore the correct figure.

As the train is accelerated from rest to 32 m.p.h. at the rate of 0.7 m.p.h.p.s., it will take $\frac{32}{0.7}$ or 45.71 seconds to reach this speed. One point on the speed-time curve is established and other points are determined by obtaining the train resistance, net tractive effort, etc., at higher speeds.

The speed-time curve—shown in Fig. 135—follows a straight line from zero to 32 m.p.h., then bends over toward the hori-

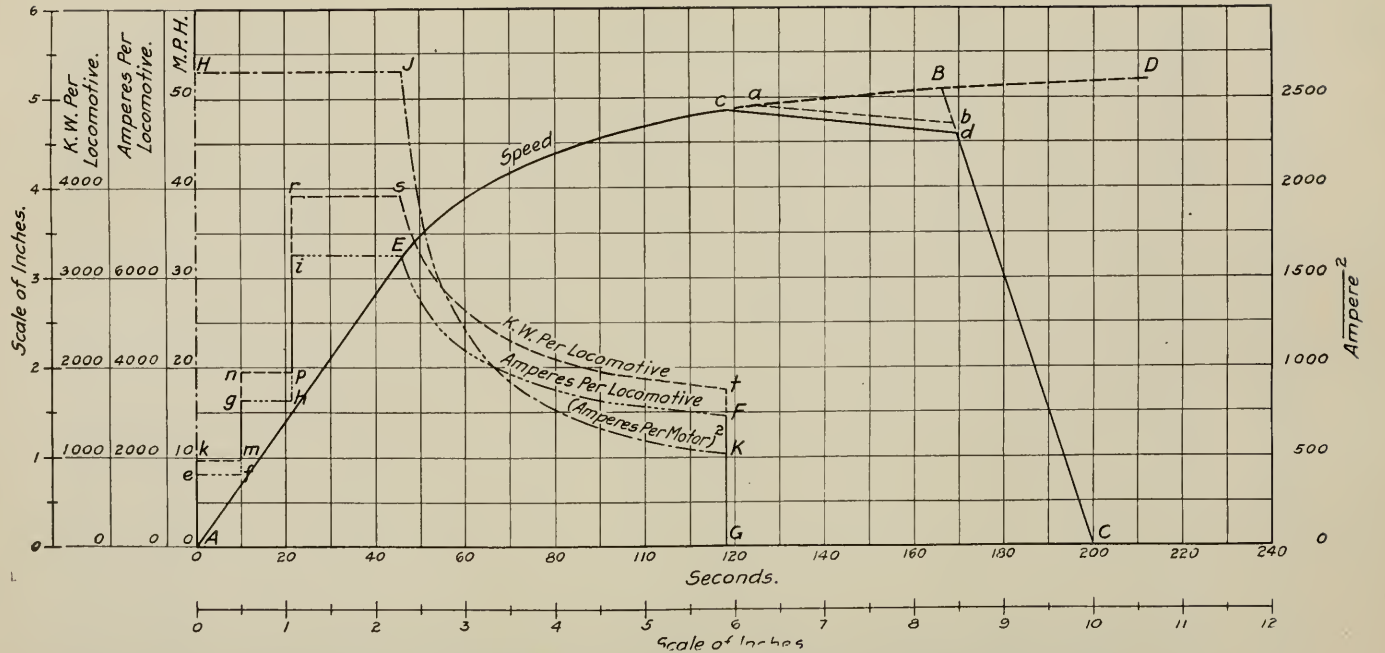


FIG. 135—Curves Showing Speed and Power Consumption Plotted Against Time.

zontal as the acceleration drops off and the train approaches a constant speed—about 52 m.p.h. in this case.

Table of Data.—When working out a problem of this kind, it will be found very helpful and time saving to tabulate data

TABLE V—DATA FOR SPEED-TIME CURVE

1 Miles Per Hour	2 Total Tractive Effort	3 Train Res.	4 Grade Res.	5 Net Tractive Effort	6 Accel.
0	13,320	1,555	685	11,090	0.7
32	13,320	1,555	685	11,090	0.7
33	12,710	1,625	685	10,410	0.647
35	10,400	1,690	685	8,125	0.505
37	8,800	1,765	685	6,315	0.392
39	7,800	1,840	685	5,275	0.328
41	6,600	1,925	685	3,990	0.248
43	6,000	2,000	685	3,315	0.206
45	5,200	2,075	685	2,440	0.153
47	4,600	2,140	685	1,775	0.110
49	4,000	2,210	685	1,105	0.069
51	3,400	2,275	685	440	0.027
52	3,300	2,300	685	315	0.019
53	3,020	2,335	685	0	0

7 Miles Per Hour	Time Increment (Sec.)	8 Total Time (Sec.)	9 Amp.	10 Amperes Squared	11 Amp. Per Loco.	12 K.W. Per Loco.
0	....	.....	.....	.....	.....	.....
32	....	45.71	1,630	2,650,000	6,520	3,910
33	1.48	47.19	1,560	2,440,000	6,240	3,740
35	3.47	50.66	1,320	1,740,000	5,280	3,170
37	4.46	55.12	1,180	1,390,000	4,720	2,830
39	5.56	60.68	1,080	1,170,000	4,320	2,590
41	6.95	67.63	980	960,000	3,920	2,360
43	8.82	76.45	900	810,000	3,600	2,160
45	11.13	87.58	820	672,000	3,280	1,970
47	15.22	102.80	760	578,000	3,040	1,850
49	22.35	125.15	700	490,000	2,800	1,680
51	41.70	166.85	650	423,000	2,600	1,560
52	43.50	210.35	625	391,000	2,500	1,500
53	105.00	315.35	600	360,000	2,400	1,440

as shown in Table V, before plotting the speed-time curve. The data in this table correspond to one motor rather than to the whole locomotive, with the exception of the last two columns where the total amperes per locomotive, and kilowatts are tabulated.

Column 1 shows the speed values chosen. The first speed is that at which the straight line acceleration stops—32 m.p.h.

—and each successive speed is not over 2 m.p.h. increase. The best results are obtained by choosing speed values so that the points on the speed-time curve will be close enough together to give a smooth curve.

Column 2 shows the tractive effort per motor corresponding to the speed in Column 1; these values are obtained from the motor curves.

Column 3 shows the train resistance per motor for a train of 633.6 tons when running at each speed, and is obtained from the train resistance curves shown in Fig. 30.

Column 4 shows the grade resistance, which is constant for all speeds. The equivalent grade for the typical run is 0.213 per cent so that throughout the typical run the train must be considered as operating against this grade. The tractive effort required per motor is 685 lb.

Column 5 shows the net tractive effort available for acceleration and is obtained by subtracting the train resistance plus the grade resistance, from the tractive effort.

Column 6 shows the rate of acceleration in miles per hour per second. The values are obtained as follows:

At 33 m.p.h. the net tractive effort per motor is 10,410 lb.; the train weight per motor is:

$$\frac{633.6}{4} = 160.9 \text{ tons.}$$

We know that a tractive effort of 100 lb. per ton will produce an acceleration of 1 m.p.h.p.s. When the train reaches 33 m.p.h. there are 10,410 lb. tractive effort for each 160.9 tons of train to produce acceleration, or, $\frac{10{,}410}{160.9} = 64.7$ lb. per ton, which gives a rate of acceleration of 0.647 m.p.h.p.s. The same applies at 35 m.p.h. so that Column 6 is obtained by dividing the net tractive effort by one hundred times the number of tons per motor.

Column 7.—As already stated the straight line acceleration will stop at 32 m.p.h., and 45.71 seconds will be required since the rate of acceleration is 0.7 m.p.h.p.s. This gives the first point on the speed time curve, and before additional points

can be determined it must be known how many seconds elapse while the train is accelerating from 32 to 33 m.p.h., etc. The number of seconds required is shown in this column and is determined as follows: At 32 m.p.h. the rate of acceleration is 0.7 m.p.h.p.s., and at 33 m.p.h. it is 0.647 m.p.h.p.s. Now if the average rate of acceleration between these two speeds which are one mile apart, is known, the number of seconds required to bring the train from a speed of 32 m.p.h. to 33 m.p.h. would be:

$$\frac{1 \text{ (m.p.h.)}}{\text{average rate acceleration}}$$

When the speed increment is small, as it is in this case, the average rate of acceleration can be taken as the numerical average of the instantaneous accelerations, Column 6, so that the time required to accelerate from 32 to 33 m.p.h. is:

$$\frac{1 \text{ (m.p.h.)}}{\frac{0.7 + 0.647}{2}} = 1.48 \text{ seconds,}$$

and from 33 to 35 m.p.h. is:

$$\frac{2}{\frac{0.647 + 0.505}{2}} \quad \frac{4}{1.152} = 3.47 \text{ seconds.}$$

A glance at the above fractions shows that the time increment can be quickly obtained by dividing twice the speed increment by the sum of the accelerations. In this particular problem where the speed increment is 2, the values are obtained by dividing 4 by the sum of the accelerations.

Column 8.—The number of seconds in this column is obtained by adding the time increment to the preceding number of seconds. For instance, it has required 45.71 seconds for the train to reach a speed of 28 m.p.h.; 1.48 seconds to go from 32 to 33 m.p.h.; 3.47 seconds from 33 to 35 m.p.h., so that the total time elapsed at 33 m.p.h. is 45.71 + 1.48 = 47.19 seconds, and at 35 m.p.h. is 47.19 + 3.47 = 50.66 seconds.

Column 9 shows the current per motor corresponding to

the speed in Column 1; the values are obtained directly from the motor curves.

Column 10.—These figures are the current values, Column 9 which have been squared. They will be plotted along with the other data and from them it will be possible to determine at what percentage of full rating the motors are being worked.

Column 11.—These values are four times those of Column 8 since the locomotive is equipped with four motors, all connected in parallel. When starting, the motors will be connected all four in series so that the current per locomotive will be only 1,630 amperes; they will then be connected in series-parallel—two motors in parallel and two sets in series—and 3,260 amperes will be taken by the locomotive. The speeds at which the changes in motor combinations take place will be discussed later.

Column 12.—In determining the power required, we have assumed that the voltage at the locomotive is constant and is 600 volts. The kilowatts are the product of amperes by volts divided by 1,000, and will also be ¼ or ½ of 3,910 when the motors are connected in series or series-parallel. This will be discussed later.

Plotting Speed and Power Curves.—The data contained in Table V, —are now ready for plotting. Referring to Fig. 135, note that the kilowatts per locomotive, amperes per locomotive, miles per hour and amperes squared (I^2) scales are all laid out with reference to seconds. A scale of inches has also been laid out for both co-ordinates.

Speed-Time Curve.—The first curve to be plotted is the speed-time curve. The data in Column 1 and Column 8 give the curve AD. The length of the typical run is 10,100 ft. and must be made in 240 seconds including the stop. Starting at 240 seconds on the zero line, draw back 40 seconds to point C, this line representing the length of the stop. The actual distance must be covered in 200 seconds so that the braking line must stop at the point C. Assume that the braking rate is 1.5 m.p.h.p.s., i.e., the speed of the train will be retarded 15 m.p.h. in 10 seconds. Starting at point, C, the braking line will cut the speed curve, AD, at point B.—Fig. 135.

The area enclosed under the speed-time curve, ABC, is a

measure of the distance covered. If the train was running at the rate of 10 m.p.h., the distance traversed in 20 seconds would be:

$$\frac{10 \text{ (m.p.h.)} \times 20 \text{ (sec)}}{3{,}600 \text{ (sec)}} = 1/18 \text{ mile or } 293.3 \text{ ft.}$$

Referring to the speed-time curve, it will be noted that the vertical scale is 10 m.p.h. to the inch, and that the horizontal scale is 20 seconds to the inch. One square inch then represents the distance traveled in 20 seconds at 10 m.p.h., or 1/18 of a mile, or 293.3 ft. The typical run is 10,100 ft. long so that the area in square inches enclosed under the curve ABC, must be at least

$$\frac{10{,}100}{293.3} = 34.43 \text{ sq. in.}$$

This area may be greater; in fact, it should be, in order that a coasting line can be provided. If the area should be exactly 34.43 sq. in. it would mean that the locomotive would be just capable of making the schedule specified in the problem, but

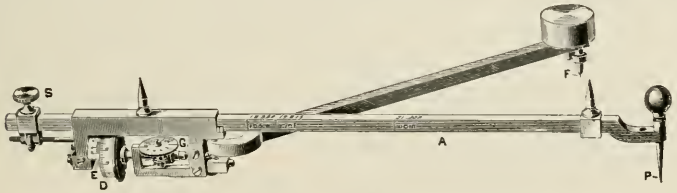


FIG. 136—Planimeter Used for Measuring an Area Having Irregular Shape.

would have no capacity for making up any time lost on account of delays. With everything working perfectly, the locomotive could make the schedule but the operation would hardly be satisfactory without some speed margin.

By means of a planimeter the area under ABC, was found to be 35.1 sq. in. The area is too great and to give the correct distance must be reduced to 34.43 sq. in. The acceleration is fixed, the time of stop and time consumed for the run is fixed, so that there is only one variable which can be changed; i.e., it is possible to cut off power from the locomotive before it reaches the speed B, allowing the train to coast. Due to train resistance, the speed of a train will be reduced

while coasting and therefore a shorter distance will be covered in the same time. The point at which the power is cut off must be determined by the "cut-and-try" method. As mentioned, the area under ABC is 35.1 sq. in., and only 34.43 sq. in. is required, a difference of 0.67 sq. in.

As a first trial, assume that the power is cut off at point *a*, which corresponds to a speed of 49 m.p.h. The force acting to produce retardation is the train resistance and the equivalent grade resistance. This is a total resistance of 2,210 + 685 = 2,895 lb., which is equivalent to 4.5 lb. per ton of train weight—100 lb. per ton would retard at the rate of 1 m.p.h.p.s., so that 4.5 lb. per ton causes a retardation of 0.045 m.p.h.p.s. For all practical purposes this coasting curve can be drawn as a straight line, although it is true that as the train slows down, the train resistance decreases and the coasting line would have a slight curvature. The coasting line is shown by *ab*. The area under the curve A*ab*C is 34.68 sq. in.. which is still greater than required, and indicates that the power can be cut off at a lower speed. Due to the very slight difference in train resistance at these speeds the coasting lines can, without appreciable error, be drawn parallel to the line *ab*. Line *cd*, starting at 48.3 m.p.h., is so located that the area A*cd*C = 34.43 sq. in. and the locomotive will make the schedule specified by cutting off power at *c*, 118 seconds from the start.

Curve of Amperes Per Locomotive.—The next step is to plot the "amperes per locomotive" curve, which stops at 118 seconds since power is cut off at this point. The data in Column 11 will give the curve from E to F. The first point given in Column 11 is 45.71 seconds. It has been assumed that the motors will be connected four in series, then in series-parallel so that the current taken by the locomotive in the first position is:—

$\frac{6{,}520}{4}$ = 1,630 amperes, and in the series-parallel position is 3,260 amperes.

In order to plot in these current values, it must be known at what speeds the changes in motor connections take place. The voltage applied to the locomotive is 600 volts. There-

fore, when the four motors are in series there is 150 volts across the terminals of each motor, and when in the series-parallel position, 300 volts across each motor. For very rough work, the speeds could be taken at one-quarter and one-half of the 600 volts speed and in this case the changes would take place at $\frac{32}{4}$ or 8 m.p.h., and $\frac{32}{2}$ or 16 m.p.h. For closer work, however, these speeds must be more carefully checked and the voltage drop in the motor must be taken into account. The relations of the speeds are obtained as follows:

$$\frac{\text{Speed in series-parallel}}{\text{Speed in parallel}} = \frac{\text{300 volts—volts drop in motor}}{\text{600 volts—volts drop in motor}}$$

and

$$\frac{\text{Speed in series}}{\text{Speed in parallel}} = \frac{\text{150 volts—volts drop in motor}}{\text{600 volts—volts drop in motor}}$$

The volts drop = IR where I = the current passing through the motor, and R = the resistance of the motor; assume that R = 0.015 ohms. Applying this formula to the present problem we obtain the following speeds:

(1) In series-parallel:

$$32 \times \frac{300 - (1{,}630 \times 0.15)}{600 - (1{,}630 \times 0.15)} = 32 \times \frac{300 - 24.5}{600 - 24.5} = 32 \times \frac{275.5}{575.5} = 15.3 \text{ m.p.h.}$$

(2) In series:

$$32 \times \frac{150 - 24.5}{600 - 24.5} = 32 \times \frac{126.5}{575.5} = 7.04 \text{ m.p.h.}$$

The remaining part of the ampere curve can now be plotted. At the start the current jumps to 1,630 amperes shown by line A*e*, and it remains at this value until a speed of 7.04 m.p.h. is reached which locates point *f*; at this speed the motors are changed to series-parallel so that the current jumps to 3,260 amperes, shown by line *fg*. The current is constant until 15.3 m.p.h. is reached, which locates point *h*. At 15.3 m.p.h. the motors go into full parallel and the current jumps to 6,520 amperes shown by line *hi*, and remains constant to point E, the end of straight line acceleration. This constant current on each step is maintained by cutting out resis-

tance; if this were not done, the current would automatically drop off as the motor speeds up.

It may be necessary to know the average current taken by the locomotive over the whole run of 240 seconds. This can be determined by dividing the area of the current curve A*efghi*EFG by 240 seconds. Referring to Fig. 117, the area of each square inch is $2{,}000 \times 20 = 40{,}000$ ampere-seconds. The area of the current curve A*efghi*EFG—obtained by the use of the planimeter—is 11.92 sq. in. so that the average current is

$$\frac{11.92 \times 40{,}000}{240} = 1{,}987 \text{ amperes.}$$

This is equivalent to taking the area and spreading it out over 240 seconds with a constant current value of 1,987.

Kilowatt Curve.—In plotting the kw. curve the values in series position will be

$$\frac{4}{3{,}910} = 977.5 \text{ kw., and in series-parallel } 1{,}955 \text{ kw.}$$

Moreover, the changes will take place at the same speeds as on the current curve. The kw. curve is shown by *kmnprst*G. It is necessary at times to know the average kw. It is obtained in the same way as the average current. Each sq. in. is $1{,}000 \times 20 = 20{,}000$ kw.-seconds. The area under the kw. curve is 14.31 sq. in. so that the average power is

$$\frac{14.31 \times 20{,}000}{240} = 1{,}192.5 \text{ kw.}$$

This value checks with the average kw. obtained from the product of the average current—1,987—and volts—600.

Current-Squared Curve.—The I^2 curve is plotted for one motor only, as connecting the motors in different combinations does not change the current values in the individual motors. The I^2 value of 2,650,000 is therefore constant from 0 to 32 m.p.h. The curve is shown by AHJKG. The object of plotting this curve is to determine at what percentage of full capacity the motors are being worked. The capacity of a motor is limited by the maximum allowable temperature of the windings; the greater the current passing through, the higher the temperature rise. The heat formed is directly

proportional, not to the actual current, but to the square of the current, since watts lost in heat equal I^2R.

The heating is therefore proportional to the average of the squares of the current values. Moreover, the square root of the average of the squared currents will be a current value which if flowing continuously through the motor would give the same heating. The square root of the average square current is known as the root-mean-square—r.m.s.—or equivalent heating current. If we know what the r.m.s. current is for a particular motor, we can tell at what per cent of total rating it is being worked, by getting the r.m.s. value from the I^2 curve. Referring to Fig. 117, the area of the I^2 curve, AHJKG, is 18.45 sq. in.; one square inch = 500,000 × 20 = 10,000,000 I^2 seconds. The average I^2 over 240 seconds is 768,750 and the r.m.s. value is $\sqrt{768,750} = 876$ amperes. The rating of the motor is 950 amperes so that it is being worked at 92.3 per cent of its capacity.

Power Required for Operation.—Electric power for propelling trains is expressed in kilowatt-hours, and it is the general practice in electric traction to specify the power required for a certain service in terms of kilowatt-hours per train-mile and watt-hours per ton-mile.

As mentioned when discussing the kilowatt curve, the area under that curve is 14.31 sq. in. Referring to Fig. 135, each square inch on the kilowatt curve represents 1,000 × 20 = 20,000 kilowatt-seconds. The total energy therefore, for this curve is 20,000 × 14.31 = 286,200 kilowatt-seconds or $\frac{286,200}{3,600} = 79.5$ kilowatt-hours. The typical run represents the average of 17 runs, so the total energy for the entire trip is 17 × 79.5 = 1,351.5 kilowatt-hours. Therefore, the kilowatt-hours per train-mile is:

$$\frac{1,351.5}{32.5} = 41.58 \text{ kw-hrs. per train-mile}$$

and the watt-hours per ton-mile is

$$\frac{41.58}{633.6} \times 1,000 = 65.62 \text{ watt-hours per ton-mile}$$

The above problem has been worked out by taking a typi-

cal run as the basis. Sometimes in new projects or on a careful study of operating conditions, it is found desirable to plot a continuous speed-time curve, etc., of a train operating over the whole line. In a problem of this kind, it would be a difficult task and require much time to work out a set of tables similar to Table 5. It is, however, possible to make a chart for the train under consideration and the various points of the speed time curve can be read directly from this chart. In the next chapter, such a problem has been assumed, the chart worked out, and its use demonstrated.

CHAPTER XXVI

THE CONTINUOUS SPEED-TIME CURVE AND TRAIN CHART

In the preceding chapter, the method used in drawing the speed-time curve, how the power consumption is obtained, as well as the percentage of work the motors of the locomotive are doing in relation to their rating, has been explained in detail. These calculations are based on the "typical run" which represents the average conditions met by the locomotive in hauling the train over the division; all the values obtained are average values. This method is quite satisfactory and is accurate enough for most problems. Sometimes, where the profile of the road varies greatly over different parts and the distance is such that considerable time is taken to pass over each of these parts, the line is divided into two or more sections and a typical run is made for each section.

There are times, however, when it is desirable to make a continuous speed-time curve over the whole profile. The labor involved in calculating all the data by the method already described would be great and the process slow; a quicker and better method, makes use of a chart from which all data can be read off directly and the points plotted therefrom, making the speed-time curve. The chart is very simple and requires only a short time to construct, as will be seen from the following description.

A problem has been assumed. From this data the chart Fig. 139 will be constructed and used to draw the continuous speed-time curve. The previous problem considered an electric locomotive hauling a train of cars; this one will consider multiple-unit train operation—a train of several motor cars all operated from one master controller.

Problem.—*Profile of a Line.*—A small section of the profile

of the line, enough to demonstrate, the use of the chart, is shown in Fig. 137.

Makeup of Train.—Seven multiple-unit motor cars.

Weight of Car Complete.—Including passengers—50 tons.

Weight of Train Total.—350 tons.

Equipment.—Two motors per car.

Diameter of Wheels.—36 inches.

Gear Ratio.—25 : 48.

Voltage at Third Rail.—600.

Accelerating current per motor.—350 amperes.

The characteristic curves of the motor used on the multiple-

TABLE VI.—300-VOLT CURVE FOR SERIES OPERATION

Speed M.P.H.	Tractive Effort 1 Motor	Tractive Effort 14 Motors	Amperes 1 Motor	Amperes 7 Motors	Amperes Sq. 1 Motor
15	2,825	39,550	350	2,450	122,500
16	2,100	30,100	280	1,960	78,400
17	1,700	23,800	245	1,715	60,200
18	1,450	20,300	215	1,505	46,300
19	1,250	17,500	195	1,365	38,000
20	1,100	15,400	175	1,225	30,600
21	1,000	14,000	165	1,155	27,200
22	875	12,250	150	1,050	22,500
23	800	10,850	140	980	19,600
24	720	10,080	130	910	16,900
25	600	8,400	120	840	14,400
26	550	7,700	115	805	13,200
27	500	7,000	105	735	11,000
28	450	6,300	100	700	10,000
29	400	5,600	95	665	9,000
30	360	5,040	90	630	8,200
31	325	4,550	85	595	7,400
32	285	3,990	80	560	6,400
33	250	3,500	77	539	5,929
34	210	2,940	75	525	5,600

unit train are shown in Fig. 138. It will be noted that speed curves are shown for both 600 volts and 300 volts. It is necessary to plot the 300-volt curve, so that the speeds and current values can be obtained for series running. The speeds at 300 volts are not exactly one-half of those at 600 volts, but are slightly less for the same motor currents, due to the greater percentage of volts drop in the motor.

Construction of Chart.—The chart is constructed from data taken from the characteristic curves. For convenience this

data is tabulated: Table 6 gives the tractive effort and amperes for one motor and for the train, corresponding to various speeds when operating in series—300 volts; Table 7 gives similar data for parallel or 600-volt operation.

Using this data, the chart, Fig. 139, can be constructed. At a point about one-third across the sheet draw the vertical line AB. To the right of this line lay off pounds tractive effort, and to the left pounds train resistance, both to the same scale. The values used in plotting the train resistance curve

TABLE VII.—600-VOLT CURVE FOR PARALLEL OPERATION

Speed M.P.H.	Tractive Effort 1 Motor	Tractive Effort 14 Motors	Amperes 1 Motor	Amperes 14 Motors	Amperes Sq. 1 Motor
33	2,825	39,550	350	4,900	122,500
34	2,500	35,000	320	4,480	102,400
35	2,255	31,150	295	4,130	86,900
36	2,050	28,700	275	3,850	75,600
37	1,900	26,600	260	3,640	67,600
38	1,725	24,150	245	3,430	60,000
39	1,600	22,400	230	3,220	52,900
40	1,475	20,650	215	3,010	41,100
42	1,250	17,500	195	2,730	38,000
44	1,100	15,400	175	2,450	30,600
46	975	13,650	160	2,240	25,600
48	825	11,550	150	2,100	22,500
50	750	10,500	140	1,960	19,600
52	650	9,100	125	1,750	15,500
54	575	8,050	117	1,638	13,600
56	500	7,000	110	1,540	12,100
58	425	5,950	102	1,428	10,400
60	375	5,250	95	1,330	9,000
65	300	4,200	85	1,190	7,400

—Curve A—for the 350-ton train are tabulated below; they were obtained from Fig. 30.

Train Resistance Data—350-Ton Train

Miles per hour	Train resistance, lb.
10	2,000
20	2,670
30	3,480
40	4,240
50	5,120
60	6,080

Using the values given in tables 6 and 7 for the tractive effort of the train, plot on the chart for both the series posi-

tion—Curve B—and the parallel position—Curve C. These curves represent the Gross Tractive Effort. Curves D and E —representing the Net Tractive Effort—are obtained by sub-

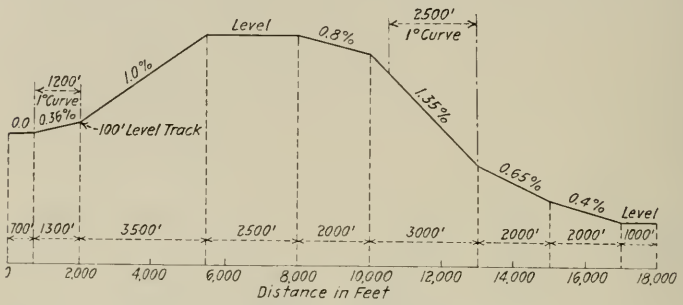


Fig. 137—Graphical Method of Showing the Profile and Alinement of a Railway.

tracting the train resistance from Curves B and C by laying off to the left the values of train resistance at several points. Gross tractive effort is the total applied at the drive wheels,

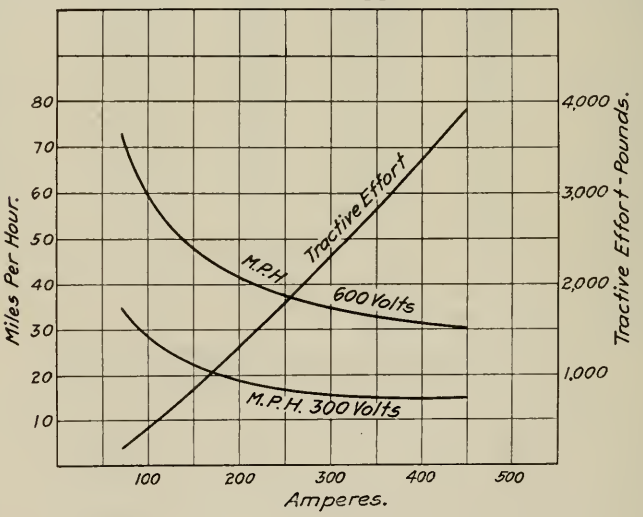


Fig. 138—Curves for Showing Motor Characteristics.

while net tractive effort is that part remaining to accelerate the train after train resistance has been overcome.

A convenient method of obtaining the points for the Net Tractive Effort curves is to take a pair of dividers, obtain the

train resistance at any speed by taking the distance of Curve A —trains resistance curve—from the vertical line AB, and then laying off this distance to the left of the Gross Tractive Effort curves. The Net Tractive Effort curves represent the tractive effort available for acceleration. Wherever these curves across the line AB, the "Zero Tractive Effort" line, the balanced speed of the train is indicated, as there is no additional tractive effort for acceleration. In the present problem, Curve D crosses the line at 32.4 miles per hour and Curve E at 57.9 miles per hour, which shows the balanced speed when running in series and in parallel on the level. When operating up or down hill, grade resistance is a factor and the above balanced speed values will be changed. It will be shown later how it is possible to obtain, directly from the chart, the balanced speed on any grade or curve.

At any point in the line AB draw a horizontal line CD which crosses AB at O. Lay off a horizontal scale of seconds, beginning at point D and a vertical scale of miles per hour per second acceleration. Draw the hyperbolas—Curves F and G—so that the product of the ordinates and abscissae is always a constant of 2 miles per hour. For instance, one point of the curve is located at the intersection of 20 sec. and 0.1 m.p.h.p.s. acceleration, as the product—20×0.1—is 2. Another is at 5 sec. and 0.4 m.p.h.p.s. acceleration—$5 \times 0.4 = 2$. This product of 2 m.p.h. will be used in plotting the speed-time curve and is the increase in speed during which the acceleration changes so little that it may be considered constant. This increment is a matter of convenience; a larger or smaller figure could be used, but 2 m.p.h. has been found convenient and is within the degree of accuracy of the problem. If any other product is used, the same increment or increase of speed is used in plotting the speed-time curve. Curves F and G are exactly alike, but are located in different quadrants on the chart.

Assume that 100 lb. per ton is required to accelerate one ton at the rate of one mile per hour per second, 20 lb. per ton additional for each per cent of grade and 0.8 lb. per ton per degree of curvature. These values are very close to the actual requirements.

The total weight of train—350 tons—multiplied by 100 gives the tractive effort—35,000 lb.—required to accelerate the train

on the level at 1 m.p.h.p.s., acceleration. Plot this value on the chart opposite 1.0 m.p.h.p.s., which gives point X. Draw a line from O, the intersection of the lines AB and CD through X. This line, OX, is called the "Acceleration on Level" line and is used for the basis for all other grades and curves.

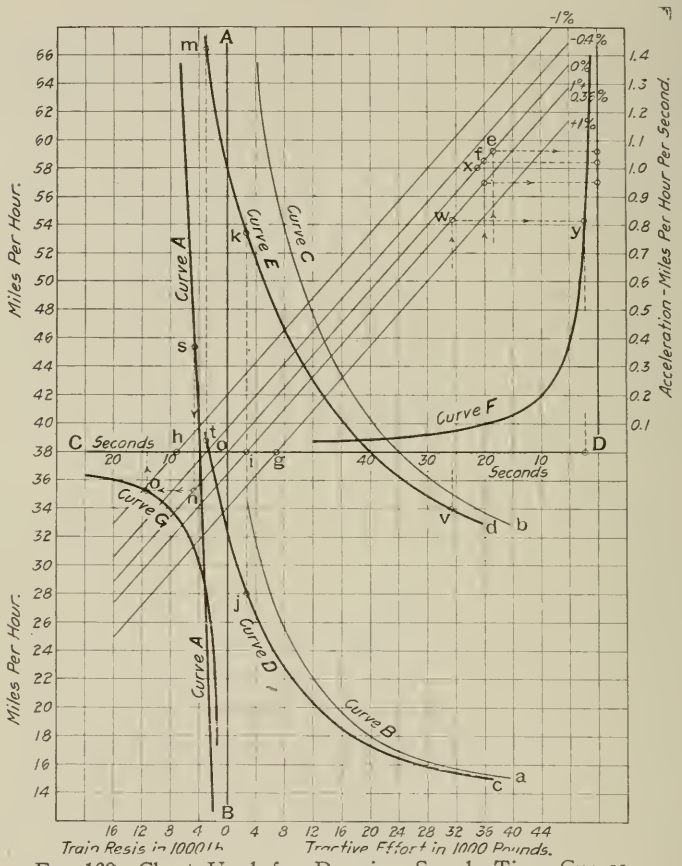


Fig. 139—Chart Used for Drawing Speed—Time Curves.

The problem stated that the average accelerating current per motor is 350 amperes, and reference to Tables VI and VII shows that a total tractive effort of 39,550 lb. is obtained when this value of current passes through each motor. The acceleration is, therefore, greater than 1 m.p.h.p.s., as only 35,000 lb. is required for acceleration at this rate. Referring to the

chart—Fig. 121—each of the Gross Tractive Effort curves —B and C—begins at a tractive effort value of 39,550 lb., points *a* and *b*. The corresponding points on the Net Tractive Effort curves, points *c* and *d* respectively, give the tractive effort available for acceleration, and if these points are projected vertically to the line OX the rate of acceleration can be obtained. Point *c*, projects to point *e*, and on the m.p.h.p.s. scale gives 1.06. Point *d*, projects to point *f*, and on the m.p.h.p.s. scales gives 1.02. This gives the acceleration of the train on the level of 1.06 m.p.h.p.s. when in series, and 1.02 m.p.h.p.s. when in parallel, with 350 amperes per motor, accelerating current.

The effect of up, or plus, grades and curves is to decrease the speed and acceleration, and the effect of down, or minus, grades is to increase the speed and acceleration. These grades and curves are taken care of on the chart by lines parallel to the "Acceleration on Level" line—plus grades to the right, and minus grades to the left. A line for each grade and curve appearing on Fig. 137 running in both directions, should now be drawn on the chart. Take for example a one per cent grade:—1 per cent $\times$ 20 lb. $\times$ 350 tons gives 7,000 T. E.—tractive effort.

Lay off this value on the line CD, to the right of O, for the plus grade and to the left for minus grade, giving points *g* and *h*. Through these points draw lines parallel to OX. As another example take the one degree curve on the 0.36 per cent grade.

0.8 $\times$ 1 $\times$ 350 gives 280 lb. T. E.
0.36 $\times$ 20 $\times$ 350 gives 2,520 lb. T. E.

Total 2,800 lb. T. E.

A curve is equivalent to a plus grade; therefore lay off this value to the right of O at point *i*. All the other lines are obtained in a smiliar way. To avoid confusion, only a few of the grade lines are shown. It has been shown that where the Net Tractive Effort curves—D and E—cross the vertical line AB, balanced speeds are reached. A similar condition holds true for grades and curves; the intersection of curves D and E, with a vertical line drawn through the point of intersection of any grade line with the horizontal CD, will give the balanc-

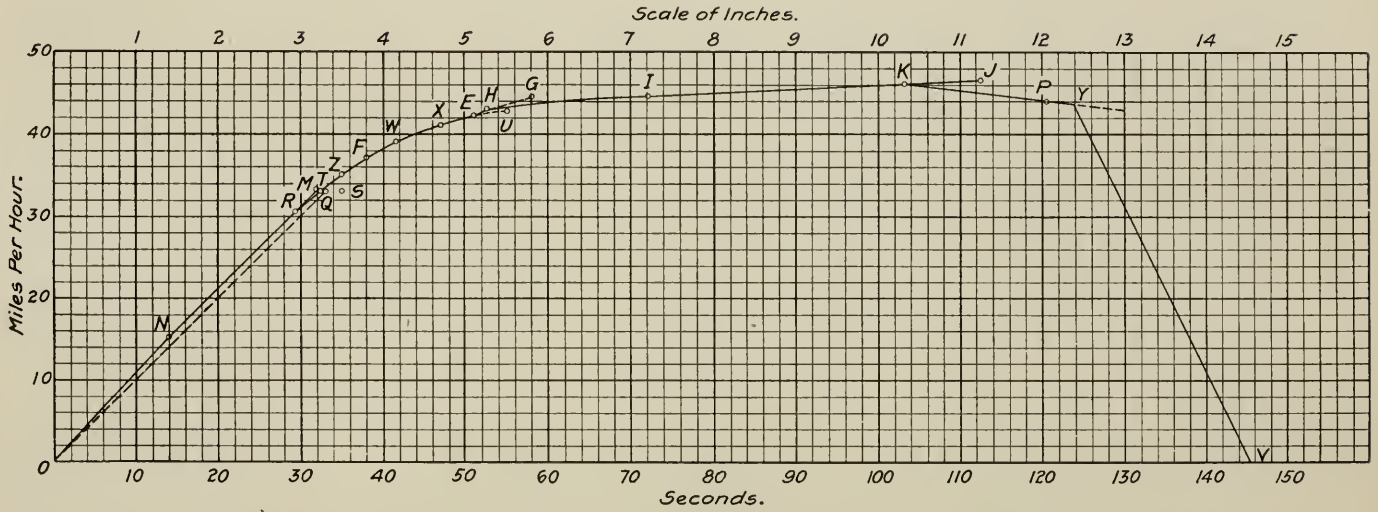


FIG. 140—A Speed-Time Curve

ing speed on that grade or curve. For example, on the one degree curve and grade of 0.36 per cent the balancing speed is where curves, D and E, cross a vertical line through *i*. In series running, it is at point *j*, or 28.1 m.p.h. and in parallel is at point *k*, or 53.4 m.p.h. On a minus 0.4 per cent grade the balancing speed in series is at point *t*, or 38.4 m.p.h., and in parallel it is at point *m*, or 66.2 m.p.h.

From the chart the continuous speed-time curve on Fig. 140 can now be drawn. Using m.p.h. as ordinates and seconds as abscissae, lay off any convenient scale. First obtain the value of one square inch in terms of distance in feet, using the scale on Fig. 140.

$$\frac{10 \text{ (sec.)} \times 10 \text{ (m.p.h.)} \times 5{,}280 \text{ (ft.)}}{3{,}600 \text{ (sec. per hour)}} = 146.7 \text{ ft. per sq. in.}$$

From motor curves—Fig. 120—at 350 amperes the motors will be in full series on the level at 15 m.p.h. In this case, using automatic acceleration, the motors will immediately go to parallel and will be in full parallel—all resistance cut out —at 33 m.p.h.

As the acceleration in series was found to be 1.06 and in parallel 1.02 m.p.h.p.s., the time taken to reach 15 m.p.h. is:

$$\frac{15.0}{1.06} = 14.1 \text{ seconds (Point N, Fig. 122)}$$

and to reach parallel or 33 m.p.h. the time required is:

$$\frac{33—15}{1.02} = \frac{18}{1.02} = 17.6 \text{ sec. more, or } 31.7 \text{ sec. from start (Pt. M).}$$

An easier and better method of obtaining line NM and one which gives exactly the same result is as follows:—
33 (m.p.h.) ÷ 1.02 (acceleration) gives 32.4 sec., the time the train would take to reach 33 m.p.h. if 1.02 m.p.h.p.s. was the acceleration throughout and which would be represented by line OQ. From point N draw a line parallel to OQ and stop same at 33 m.p.h.; this line will coincide with the line NM.

The acceleration cannot, however, continue uniformly to 33 m.p.h., because the train strikes a grade and curve. Re-

ferring to Fig. 137, the one degree curve and 0.36 per cent grade begin at a point 700 ft. from the starting point. One square inch on Fig. 140 represents 146.7 ft., so that 700 ÷ 146.7 = 4.77 sq. in. under the line ONM will give a point R on NM at which the acceleration will change. A planimeter is used for obtaining this area and thereby determining point R.

To obtain the slope of the line refer to the chart, Fig. 139. Project the point where the vertical line through *d* cuts the 1 degree curve + 0.36 grade line, to the scale of acceleration, which gives 0.95 m.p.h.p.s., which is the acceleration on this curve and grade. Obtain the slope of line on Fig. 140 as previously described for NM thus: 33 (m.p.h.) ÷ 0.95 (accel.) gives 34.8 seconds, which locates point S. Draw a line through R parallel to OS, and end it at 33 m.p.h. (point T), because this speed represents the end of straight-line acceleration due to the motor characteristic.

Further calculations will involve a constantly changing acceleration, but good results can be secured by dividing the speed changes into steps of 2 m.p.h.; for this the curves F and G—Fig. 139—simplify the work.

The level track ended at R, and there follows 1,200 ft., or 1,200 ÷ 146.7 = 8.16 sq. in. on Fig. 140 of the curve and grade. Take an increment of 2 m.p.h. above the 33 m.p.h.—35 m.p.h.—and use the average of these two speeds, or 34 m.p.h. The point corresponding to 34 m.p.h. on Curve E, is point *v*—Fig. 139. Project point *v* to the 1 degree and 0.36 per cent line, point *w*; and to hyperbola curve F, point *y*; to scale of seconds which gives 2.4 seconds required for the 2 m.p.h. increase.

On speed-time curve—Fig. 140—locate point Z, 2.4 sec. beyond point T, and at 35 m.p.h. The middle point of the next 2 m.p.h. increment is 36 and by the same procedure, 3 seconds time is required to reach 37 m.p.h.—point F; points W, X and U are obtained in the same way.

The area under the curve between points R and E is 8.16 sq. in. Therefore the train leaves the curve at point E at 42 m.p.h., to run on straight and level track. The rate of acceleration will be greater and the speed curve will follow the line EG.

Referring to Fig. 137: There is a distance of only 100 ft.

before a 1 per cent grade is reached, therefore, the area under the curve beyond point E will be 100 ÷ 146.7, or .68 sq. in., which locates point H at 42¾ m.p.h. Proceed with the increment of 2 m.p.h. from this point—42¾ m.p.h.—using the 1 per cent grade line, which will give another slope, and points I and J are obtained and plotted. The point for the top of the grade is obtained by using the area below the speed-time curve, as has been previously explained, and is designated as point K.

Assume that the train uses no power after reaching the top of the grade and coasts into the station: To obtain the coasting line, starting from point K, refer to Fig. 130. At the time the current was shut off the train was running at 46¼ m.p.h.; the middle point of a 2 m.p.h. decrease in speed is 45¼ m.p.h. which locates point *s*, on curve A. Project this point to the "Acceleration on Level" line—or if coasting on a grade to the corresponding grade line—giving point *n*; project *n* to hyperbola curve, G, giving point, *o*; project *o* to CD, which gives 14 seconds, or the time required for a 2 m.p.h. decrease in speed while coasting. At 14 seconds beyond point K on the speed-time curve—Fig. 140—and at 44¼ m.p.h., plot point P. A line through points K and P gives the slope of the coasting line, which may be extended until it is necessary to apply the brakes to bring the train to a stop at the proper point.

Assume a braking rate of 2 m.p.h.p.s., which is represented by the slope of line YV. The station stop—Fig. 137—is 2,000 ft. from the point where the current is shut off. Therefore it is necessary, by trial, to locate the point Y where brakes are applied, so that the area under the curve K-Y-V is equal to 2,000 ÷ 146.7, or 13.63 sq. in.

The speed-time curve for the rest of the profile on Fig. 137 may be continued in the same manner. The train, on leaving the station, would accelerate on the level for a few hundred feet and then descend an 0.8 per cent grade. It will of course be necessary to draw, on Fig. 139, additional lines parallel to OX, to take care of each value of grade and curvature encountered, but otherwise all values can be obtained from curves and data already on the chart.

In connection with the speed-time curve, draw in the power

curve and the ampere-square curve, as was described in the previous chapter.

Additional Points—Speed-Time Curve.—The speed-time curve represents the operating condition and shows graphically the typical run. The curve is made up of four variables —acceleration, coasting, retardation or braking, and stop. A change in any one of these factors will change the schedule speed, the other three remaining the same; or, for the same schedule, a change in one of the variables may change one or all of the other three. A change in power consumption may also occur. In the study of electric traction, it is necessary to have a clear understanding of these four factors and their relation. Gear ratio also has an effect on the speed-time curve. Many times, the motor curve is not suitable; the speed may be too high or too low; in any case it can be changed to suit the conditions by changing the gear ratio to one which is suitable for the particular service.

It requires one hundred pounds per ton tractive effort to produce an acceleration of one mile per hour per second; other rates of acceleration are proportional. Therefore, at low rates of acceleration the tractive effort will be less and hence the current will be less than for high rates. It naturally follows that the time will be greater to reach a certain speed, and moreover, a greater distance will be covered before attaining this speed—the lower the rate of acceleration the less will be the distance travelled in a given time. In locomotive operation, especially in long runs, the rate of acceleration is not an important factor, as the time of acceleration is only a small part of the total run. However, in suburban service, in which multiple-unit trains are generally used, the operation is on a high speed schedule, and usually stops are many and close together. Under these conditions the time gained or lost during acceleration may be an important item in the maintaining of schedules. This situation prevails in the suburban service of the New York Central, where a large proportion of the traffic is handled by multiple-unit trains. In the electrification of the Pennsylvania at Philadelphia, no locomotives are used; this is also true of the Long Island Railroad and the West Jersey and Seashore Railroad.

As it takes longer with low acceleration to reach a certain

speed, it will be necessary to keep the power on the locomotive for a longer time, so that to maintain a certain schedule there must be less coasting. Also the train will be running at at a higher speed when the brakes are applied. This is illustrated in Fig. 141; the speed-time curve, OABCDE, represents a typical run. Assuming a lower acceleration under these conditions, the speed-time curve will be ORSTDE. The area enclosed under the speed-time curve is a measure of the dis-

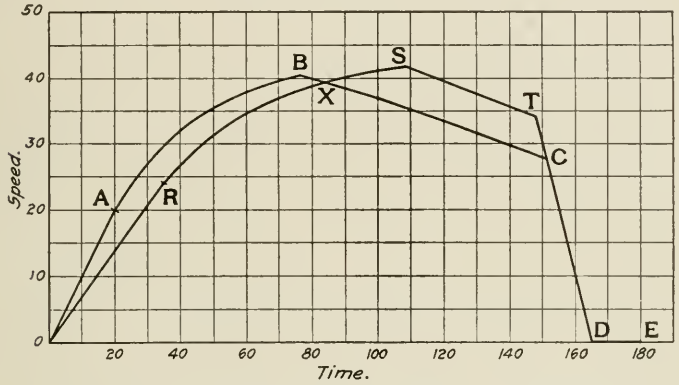


FIG. 141—Curves Which Show the Effect of Changing the Rate of Acceleration.

tance covered. Since it is desired to perform the same schedule with the two different rates of acceleration, the areas underneath the two curves must be equal. Due to the lower acceleration, however, area is lost during the first part of the run; this lost area is OABXR, in Fig. 141. Therefore, to compensate for this loss, the power must be kept on longer than would be necessary with a higher acceleration, so that the rising part of the curve is extended to a point that makes the area, XSTC, equal to the area OABXR.

The amount of power the train will require depends largely on the rate of acceleration. In the case of long runs, as mentioned before, a change in acceleration will make only a small change in the power consumption, since the percentage of increase is very small, but in short runs the increase in power consumption may be considerable. Generally, the higher the speed at which brakes are applied, the greater the power consumption. A train running at a certain speed develops a cer-

tain amount of kinetic energy; this energy is used to propel the train after the power is cut off and thus permits coasting. If the train is retarded at a constant rate, then, the higher the speed at which brakes are applied, the greater will be the power consumed by the brake, and the greater must be the energy input to offset this loss.

In a previous chapter it was shown that the heat developed in a motor is dependent upon the square of the current passing through the motor. Increasing the acceleration increases the current, causing an increase in the heating. However, with increased acceleration the power is on a shorter length of time, tending to reduce the heating. For any given run there is a rate of acceleration which will give the minimum heating. Rapid acceleration affects the heating of the motors to a much greater extent in short runs than in long runs, as the high currents occur more frequently and form a larger proportion of the total time. Since heating depends upon the root-mean-square current, the heating is, in general, less as the run is longer. The size of the motor is determined by the heating, so that with a given weight of car, and a given schedule, larger motors are required as the number of stops increase.

A study of the speed-time curve will show that the length of stop will have a decided effect upon the schedule speed and the power consumption. If the stop is lengthened the point D, will be moved nearer the point O, and in order to keep the same area the power must be on longer, with less coasting, so that there will be an increase in power consumption and heating will also be increased.

A change in the braking rate will affect the operation in a manner similar to effects produced by a change in acceleration; in long runs a change in the braking rate only slightly affects conditions since the time of braking is a small proportion of the total time of the run, but in short runs it becomes an important factor. A high braking rate is advantageous as it allows more coasting; the train is allowed to coast right up to the last possible moment and in maintaining a certain schedule, the power can be cut off sooner—approximately the amount of time saved by the more rapid braking.

CHAPTER XXVII

GEAR RATIO AND WHEEL DIAMETER

The gear ratio between the motors and the car wheels determines the speed of the train—with constant voltage and assuming a variable speed motor. The tractive effort, with a constant current flowing through the motors, also depends on the gear ratio.

Gear Ratio.—The speed and the tractive effort are directly proportional to the gear ratio and it follows that with a high speed the tractive effort is low. Therefore, to produce a given tractive effort or a certain rate of acceleration with high-speed gearing a much greater current must be used than is required with low-speed gearing. More power is thus required on grades and curves, but the time consumed will be decreased—one advantage of high gearing. It is possible, however, to gear for too low a speed, so that the amount of coasting will be so small that the power consumption will be excessive. In general, a gear ratio should be used which will give the lowest speed required to maintain the schedule, allowing ample margin for making up lost time. In studying a problem and drawing up the speed-time curve, allowance should be made for sufficient coast to take care of delays, etc., so that the equipment can operate on a faster schedule when all conditions are perfect. There should be at least 10 per cent allowance for coasting, but operating conditions may be such that 15 or 20 per cent allowance may be necessary.

The changing of the motor curve from one gear ratio to another is a simple procedure and is as follows:

Characteristic curves of a railway motor are shown by the

full lines in Fig. 142. These curves are drawn for a gear ratio of 21:66 with 33 in. wheels. As an illustration of the procedure assume that the speed is too high and it has been decided to use a 16-tooth pinion; the new ratio would then be 16:71. It should be mentioned here that the sum of the pinion and gear teeth is always the same for any one motor when the same pitch is used. The total number of teeth is fixed by center distances, i. e., the fixed distance between the center of the armature shaft and the center of the driving wheel axle.

The curves in Fig. 142 are drawn in reference to amperes per motor. At any given current the armature revolutions of the motor will be constant so that with the 16-tooth pinion the revolutions of the axle, and therefore the speed, will be less than with the 18-tooth pinion. The gear ratio is equal to $\frac{\text{Number of gear teeth}}{\text{Number of pinion teeth}}$. The speed will vary inversely as the gear ratio and therefore, in this problem, will vary as:—

$$\frac{\frac{66}{21}}{\frac{71}{16}} = \frac{3.14}{4.44} = .708$$

By taking various points along the m.p.h. curve and multiplying by the factor .708 a new speed curve—shown by dashes —is obtained.

The horsepower for a constant current is constant so that the tractive effort will be increased with the new ratio of 16:71. The amount of increase will be directly proportional to the ratio of the gear ratios and in this case will be $\frac{4.44}{3.14} = 1.41$. Applying this factor to the T. E. curve a new curve is obtained as shown by the dotted line. These new

curves—shown by dashes—can now be used for the problem which may be under consideration.

Wheel Diameter.—A change in wheel diameter will also affect the speed and tractive effort. Changing to a 36-in. wheel increases the speed for a constant current and must therefore decrease the tractive effort. Assuming the original gear ratio of 21 : 66 and that the equipment is mounted on

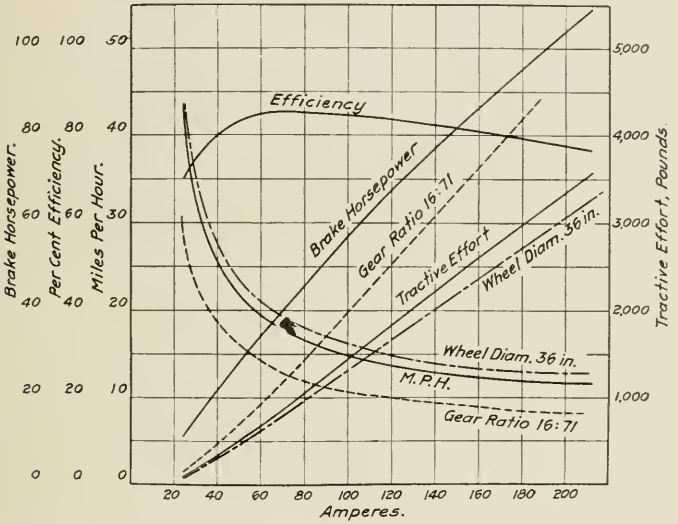


Fig. 142—Motor Characteristic Curves Showing Effect of Changes in Gear Ratio and Wheel Diameter.

36 in. wheels instead of 33 in., determine the characteristic curves to use. The factor for the speed is determined as follows by the ratio of $\frac{36}{33} = 1.09$, and for the tractive effort by the inverse ratio, namely $\frac{33}{36} = .917$. Applying these factors to the curves, new curves are obtained, as shown by the dots and dashes. If it is necessary to make changes for both

wheels and gear ratio the following formula will be used having in mind that:

$$\text{Gear ratio} = \frac{\text{Number of gear teeth}}{\text{Number of pinion teeth}}$$

$$1.\ \frac{\text{M.P.H. (1)}}{\text{M.P.H. (2)}} = \frac{\text{Gear Ratio (2)}}{\text{Gear Ratio (1)}} \times \frac{\text{Wheel Diam. (1)}}{\text{Wheel Diam. (2)}}$$

$$2.\ \frac{\text{Tractive Effort (1)}}{\text{Tractive Effort (2)}} = \frac{\text{Gear Ratio (1)}}{\text{Gear Ratio (2)}} \times \frac{\text{Wheel Diam. (2)}}{\text{Wheel Diam. (1)}}$$

CHAPTER XXVIII

AN ELECTRIFICATION PROBLEM—I

In this chapter and the chapter following will be worked out a complete electrification problem, showing what information is necessary and how it is used. The discussion will, necessarily, be of a general nature as every problem is so different in detail, but the method described can be applied to any problem relating to the electrification of steam railroads. In the application of this method, the data assembled in the preceding chapters in describing the calculations for tractive effort, train resistance, etc., will be employed.

Assume that on a steam railroad, operating both passenger and through and local freight trains, over a profile which is not level, a study is to be made for the purpose of electrification. Certain data is necessary to determine the most suitable design of electric locomotive; the power required from the power house to maintain the schedule; the maximum load on the power house, etc.

There are several factors which should be considered in the selection of the electric locomotive equipment; some of these factors, at first thought, appear unimportant. It is an easy matter to choose a locomotive that will be more than large enough to perform a given service, but to select one that is just the right size, one that is of minimum first cost and minimum weight, requires careful study.

The motors of an electric locomotive must be capable of exerting a certain number of pounds tractive effort at the driving wheels to pull a trailing load of a certain number of tons. It has been established that, on level track, it requires a tractive effort of from fifteen to twenty-five pounds per ton of trailing load to start a train and bring it up to speed; about seven pounds is the tractive effort per ton required

to maintain this train at constant speed. The actual tractive effort that a locomotive, for a particular service, must be capable of exerting depends on the condition of the track, the curves and grades, on the number, condition, and weight of cars in the train.

The weight of a locomotive must be such that the adhesion to the rails is sufficient to enable the motors to exert their normal tractive effort. If the locomotive is too light, the wheels will slip when an attempt is made to start or to pull up a grade a load which otherwise would be within the capacity of the equipment. The maximum tractive effort of the locomotive is limited by its weight and is not determined wholly by the torque of its motors. The locomotive should not, however, be too heavy for its motors; if the weight on the drivers is excessive, the motors will be overloaded before the drivers will slip. Therefore the weight of the locomotive should be properly proportioned in relation to the power of the motors and the service conditions, so that the driving wheels will slip if an effort is made to draw an excessive load. With this relation, the motors are automatically protected from excessive overload in starting. From this, it is obvious that a careful study must be made of the grade and traffic conditions, in order to select the most suitable locomotive.

The Railroad's Tonnage Records.—Every railroad keeps a record of the tonnage hauled and the number of trains operated. The tonnage and the number of trains vary from day to day. Therefore, in considering electrification, the records of the existing steam operation must be studied carefully so as to ascertain both the maximum and the average day. The characteristics of the steam locomotive should also be studied to get an idea of the power required to handle the tonnage trains.

The maximum day is the 24 hours during which the maximum tonnage is hauled and the greatest number of trains are operated. The average day is the schedule and the tonnage which would represent the average business handled by the railroad over a long period—several months or possibly a year or more. The data for the maximum day is necessary in order to determine the total number of locomotives re-

quired, and also the total power required. It is this data, also, from which the capacity of the power house and location of the substations would be determined. From the average day the average results can be calculated and an estimate made of the power that will be required over a given period.

On nearly every railroad the business is increasing constantly. A curve showing the growth can be plotted from the data available and an estimate of the freight and passenger business to be handled in the near future can be obtained by extending the curve. The maximum day can also be obtained in the same way, as generally there is a direct relation existing between the maximum day and the average day. It may be necessary to vary this procedure, as it is difficult to lay down any fixed rules for determining the maximum and average day, inasmuch as each railroad problem generally is different from every other one. Many times assumptions must be made and, naturally, a close study of the conditions existing on a given railroad will permit conclusions nearer to actual than could be obtained from assuming certain specific general conditions. It is always advisable to confer with the railroad officers, regarding the effect that improvements in operation, which will be secured by electric traction, will have on the schedule, tonnage hauled, etc.

The Train Sheet.—The maximum as well as the average day is represented by a diagram known as the "train sheet". The train sheet, with time as a base and distance as the ordinate, shows graphically the service handled over the railroad. For example, assume that the train sheet shown in Fig. 143 represents part of the operation for the average day, with electric locomotives, on the railroad under consideration. The train sheet for steam operation for an average day would be similar, so that this particular sheet could represent steam operation, providing the steam locomotive was capable of exerting the same draw-bar pull at the same speed as the electric locomotive chosen for the service.

In this train sheet the distance between the terminals of the division under consideration is 100 miles. Between the terminals A and E, are intermediate points, B, C, and D, where some of the through freight trains stop; local freight trains

also stop at these points and at the additional points, *m*, *n*, *p*, *s* and *t*.

The Profile.—Before the train sheet can be plotted for electric operation, the profile of the railroad must be known and the characteristic curves of the electric locomotive chosen must be available. The profile used is not the actual profile of the road, but is the average grade profile. To explain: over a distance of 100 miles, there would be, normally, a multitude

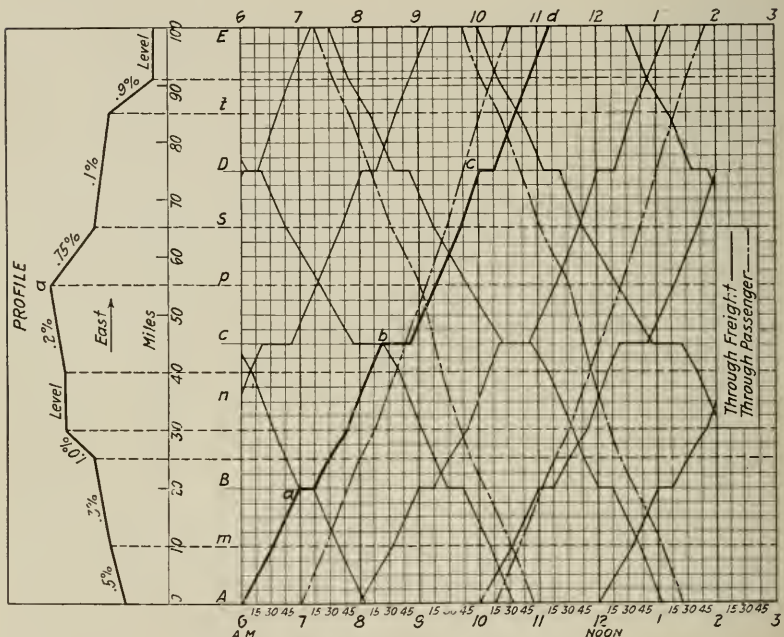


Fig. 143—Example of a Train Sheet.

of grades and curves of short distance. The use of the train sheet is such that it is not necessary to consider every grade but only the average grades. A study of the profile will show that it can be divided into a few ruling or average grades. Although there may be many grades between two points, there is an average grade between these two points; this average grade is used in constructing the train sheet. The average grade of a section of track connecting two points is the ratio of the difference in elevation of these two points

and their distance apart, measured in the same unit; usually this is expressed in per cent. There may, however, be a sharp grade of sufficient length to determine or at least influence the choice of the electric locomotive. If so, this grade should be used separately, not averaged with the other grades.

A very convenient arrangement, is to draw the average profile to the left of the train sheet, using as the base the distance as in Fig. 143. With the profile so located, it can be seen at a glance just where any train is at any time and it also aids in the drawing of the train sheet. For the purposes of this problem, the average profile shown at the left of Fig. 143 is assumed.

Characteristic Curves of Locomotive.—Having drawn the average profile, other data required are the characteristic curves of the electric locomotive, chosen for the service. Assume that the railroad has both freight and passenger service, but that, as there are only a few passenger trains, the freight locomotive can be also used for passenger service. On a railroad where the service required a passenger locomotive an additional set of characteristic curves would be necessary. These would be referred to when considering passenger train operation.

From the study of the operating conditions a wide variation is found in the size of the freight trains handled by steam. The through freight business is heavy and the traffic handled could be increased greatly with electric operation, providing trains of 3000 tons were made up. The local service is much lighter and would not exceed 1500 tons. It, therefore, would be most economical to select a locomotive capable of handling the 1500-ton train and then use two such locomotives on the 3000-ton train.

A 1500-ton train operating on a profile, which has a maximum grade of 1 per cent, would require a draw-bar pull when running on the grade of $1500\ (20 + 6) = 39{,}000$ lb.—the 20 lb. represents the 1 per cent grade resistance and the 6 lb. the train resistance. Since the 1 per cent grade is of considerable length, it might sometimes be necessary to start the train on this grade so that the locomotive must have sufficient weight to give the necessary adhesion and adequate

motor capacity to meet this condition. The starting of a 1500-train on the 1 per cent grade at an acceleration rate of 0.1 m.p.h.p.s. requires 10 lb. per ton additional to the grade and train resistance. The total draw-bar pull required then will be 39,000 + 15,000, or 54,000 lb. The tractive effort required of the motors will be greater than the draw-bar pull by an amount equal to that required to accelerate and to move the locomotive itself up the grade. With this information and assuming a factor of adhesion of 4, it is found that a locomotive weighing 150 tons, with the total weight on drivers, will be satisfactory. The total tractive effort required will then be 54,000 + 150 (20 + 15 + 10) = 54,000 + 6,750 = 60,750 lb.

The size and the weight of the locomotive to handle the 1,500-ton trains has now been determined, but, as already mentioned, 3,000-ton trains would be most economical for through freight service. This size of train could be handled by two locomotives operating in multiple by the multiple unit system, as easily and as readily as the 1,500-ton train with one locomotive.

System of Operation.—Up to this point no mention has been made of the system to be used in the electrification problem under consideration. There are several systems to choose from: the 600-volt direct-current; the 1200-1500 volt direct-current; the 2400-3000 volt direct-current; the 11,000 volt single-phase; and the 11,000 volt split-phase.

The 600-volt direct-current system would not be suitable on account of the low voltage. The systems which would be seriously considered are the 2,400-3,000 volt direct-current, the 11,000 volt single-phase and the 11,000 volt split-phase.

To determine the most economical operation, each system must be applied to the problem and complete data worked out for each. Costs, power consumption, estimates of maintenance costs, etc., must be obtained and all worked down to the percentage return on the net investment. Of the three systems, the locomotives used in two of them have the variable speed characteristics and the third, constant speed. The direct current and the 11,000-volt single-phase are variable speed, i. e., the speed decreases when the load increases and vice versa. The split-phase locomotives are equipped with the

three-phase induction motors and operate at a constant speed regardless of the grade and load.

To illustrate how the train sheet is constructed, assume that the system to be used is 3,000 volts direct current. With the variable speed locomotive, used with this system, different speeds are obtained on different grades and it is, therefore, more difficult to construct the train sheet for a direct current

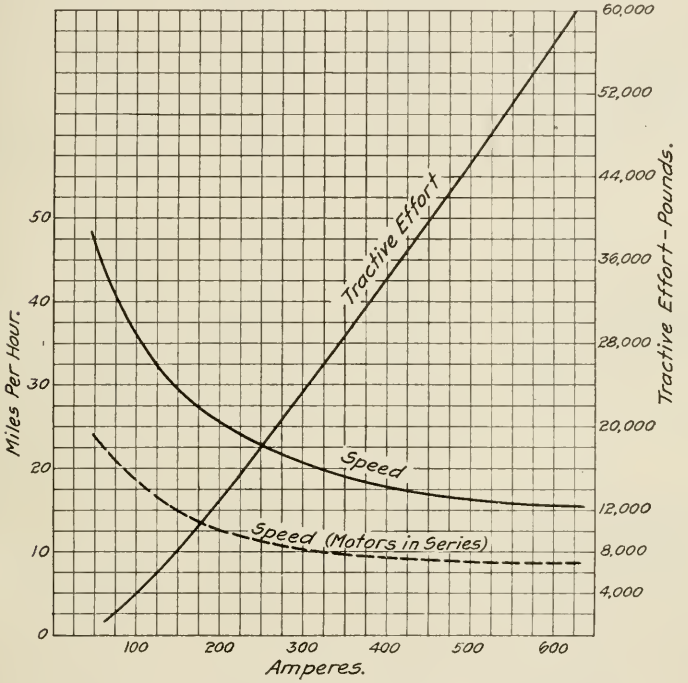


Fig. 144—Characteristic Curves of an Electric Locomotive.

system that it would be for a system using a constant speed locomotive.

To construct the train sheet, the characteristic curves of the 3,000-volt 150-ton locomotive must be available. These curves are shown by Fig. 144. Fig. 143, is only a part of the train sheet, as all trains for a period of 24 hours are not shown —only trains operating from 6 a.m. to 2 p.m.

At 6 a.m. a through freight train of 3,000 tons leaves ter-

TABLE VIII—DATA FOR LOAD CURVE

	Grade Per Cent	Amperes per Train	Power K. W. Amp. × 3000 V / 1000	Speed M. P. H.	Minutes
Through Freight 3000 Tons, East	+0.5	690	2070	19	32
	+0.3	570	1710	21.5	42
	+1.0	990	2970	16.5	18
	Level	370	1110	26.5	23
	+0.2	500	1500	23	39
	—0.75	...	....	25	24
	—0.1	290	870	30	40
	—0.9	...	....	25	14
	Level	370	1110	26.5	20
Through Freight 3000 Tons, West	Level	370	1110	26.5	20
	+0.9	925	2775	17	21
	+0.1	440	1320	24.5	50
	+0.75	830	2490	17.5	34
	—0.2	110	330	18	50
	Level	370	1110	26.5	23
	—1.0	...	....	25	12
	—0.3	60	180	22.5	40
	—0.5	...	....	25	24
Through Passenger 800 Tons, East	+0.5	240	720	23	26
	+0.3	200	600	26	35
	+1.0	325	975	20	15
	Level	140	420	31	20
	+0.2	180	540	27	33
	—0.75	...	...	30	20
	—0.1	110	330	35	34
	—0.9	...	...	30	12
	Level	140	420	31	18
Through Passenger 800 Tons, West	Level	140	420	31	18
	+0.9	310	930	20	18
	+0.1	160	480	29	42
	+0.75	285	855	21	29
	—0.2	90	270	37.5	24
	Level	140	420	31	19
	—1.0	...	...	30	10
	—0.3	33	99	22	41
	—0.5	...	...	30	20

minal A and also one from terminal E. First consider the train leaving A. A 0.5 per cent grade is first encountered; the tractive effort required by this grade is 3,000 (10 + 6) = 48,000, to which must be added the locomotive tractive effort, which is 300 (10 + 15) = 7,500 making a total of 55,000 lb. Two locomotives are used on the 3,000-ton trains, so that the tractive effort per locomotive is 27,750 lb. Referring to the locomotive characteristic curves, the speed and current corresponding to 27,750 lb. tractive effort are 19 m.p.h. and 345 amperes respectively. The total of 345 amperes is for one locomotive only so that the current taken from the line for operating the 3000-ton train would be 690 amperes. The length of the 0.5 per cent grade is 10 miles, so that the time consumed to *m* would be $\frac{10}{19}$ of 60, or 32 minutes, approximately. A line drawn from 6 a.m.—Sta. A—to 6:32 a.m.—Sta. *m*—represents the train running over this grade. While working out the train sheet a tabulation should be made of the power consumed for the different trains operating over the various grades, as this information is required when drawing the load curve on the power house. The tabulation is shown in Table VIII.

From Station *m* the freight train will operate against a 0.3 per cent grade. Following the same procedure as on the 0.5 per cent grade, the tractive effort required will be 3000 (6 + 6) + 300 (6 + 15) = 36,000 + 6,300 = 42,300 lb. Referring to the locomotive curve, the speed and current corresponding to a tractive effort per locomotive of 21,150—one-half of 42,300—are 21.5 m.p.h. and 285 amperes. The total current for the train would be twice 285 or 570 amperes. The length of the 0.3 grade is 15 miles, so that the time required to reach the end of the grade would be $\frac{15}{21.5} \times 60 = 42$ minutes. It is assumed, however, that the through freight trains are required to stop at Station B for a short period—an average of 15 minutes. The time to reach B would be 28 minutes, or clock

time of 7 a.m. The train will leave B at 7:15 a.m. and reach the end of the grade 14 minutes later, or at 7:29 a. m.

On the 1.0 per cent grade the tractive effort needed will be $3{,}000\ (20 + 6) + 300\ (20 + 15) = 78{,}000 + 10{,}500 = 88{,}500$ lb. The speed and the current corresponding to this tractive effort are 16.5 m.p.h. and 495 amperes per locomotive, or 990 for the train. The time required on the grade will be $\frac{5}{16.5} \times 60 =$ 18 minutes—approximately.

On the level stretch the locomotives have only to overcome train resistance. The tractive effort will be $(3{,}000 \times 6) + (300 \times 15) = 18{,}000 + 4{,}500 = 22{,}500$ lb. The speed corresponding to 11,250 lb.—the tractive effort per locomotive—will be—referring to the locomotive curves—26.5 m.p.h. and the current for the train will be 370 amperes—185 amperes per locomotive. The time required to reach the end of the level stretch of ten miles will be $\frac{10}{26.5} \times 60 = 23$ minutes—approximately.

The time required on the other grades is obtained in the same way and is tabulated with the data in Table VIII. In the case of the train running east, the maximum allowable speed down the 0.75 per cent and 0.9 per cent grades is 25 miles per hour. On the 0.1 per cent grade the train resistance is greater than the force acting to pull the train down hill on account of the grade. The downward pull in lb. per ton is $\frac{1}{10}$ of $20 = 2$ lb. The train resistance of the trailing load is 6 lb. and of the locomotives 15 lb.; the total tractive effort is $3{,}000\ (6 - 2) + 300\ (15 - 2) = 12{,}000 + 3{,}900 = 15{,}900$ lb. The corresponding speed is 30 miles per hour. The total current is $(2 \times 145) = 290$ amperes.

The data—Table VIII—are plotted, completing the run of the 3,000-ton freight train to Station E. A longer stop is made at C than at B and D. Assuming that a 3,000-ton freight train is despatched east every two hours, there would then be a series of lines exact duplicates of the line, *a b c d*, but two hours

apart; these lines have been drawn in on the chart. Also assume that the freight traffic west is made up of 3,000-ton trains despatched every 2½ hours. The data for the plotting of the lines, representing the trains operating west, is obtained as explained for eastbound trains and is tabulated in Table VIII. The first train line between the Stations E and A is that of the freight train leaving E at 7:30 a.m. and all of the other train lines are parallel to it, and 2½ hours apart.

If the train was operated westward down the 0.2 per cent and 0.3 per cent grades with the controller full-on the speed would be over 30 m.p.h., which is excessive. On the other hand, the grades are not steep enough to cause the train to roll down hill without power. Operating with the motors in series gives a satisfactory speed for the grades and the sharp curves which exist on this part of the division. The speed curve, with the motors in series, is shown by the dotted curve and the current required will be one-half of that required when the motors are in parallel. The speeds, etc., for the train operating down these grades in series are included in the data in Table VIII.

Assume that between 6 a.m. and 2 p.m. there are two through passenger trains each way, each train having a total weight of 800 tons and making no stops. The lines representing these trains are drawn in by exactly the same method as in the case of the through freight trains described in the preceding paragraphs. One locomotive only is required for these trains. The data is tabulated in Table VIII. On the steep down grades a higher speed is permissible with these lighter trains.

From the train sheet the "Load Chart" can be drawn. The train sheet as shown is not complete; there should be included local passenger and local freight trains. These have been left out purposely, so as not to cause confusion which might exist with a great many train lines. The lines for the local passenger and local freight trains would be plotted in the same way and from similar data. They would not affect, in principle, the drawing of the "Load Curve". The construction of the "Load Chart" is described in the next chapter.

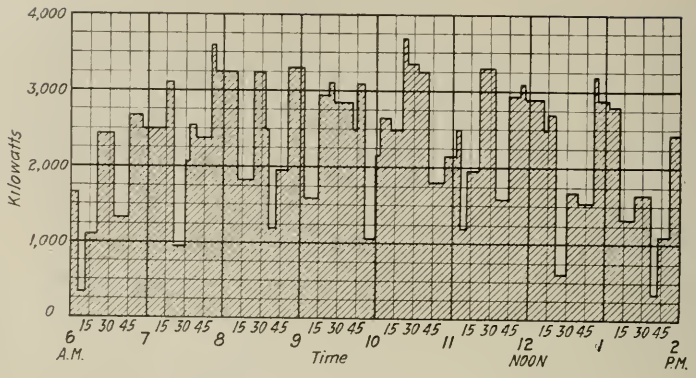


Fig. 145—Example of a Load Curve—Trains Westbound.

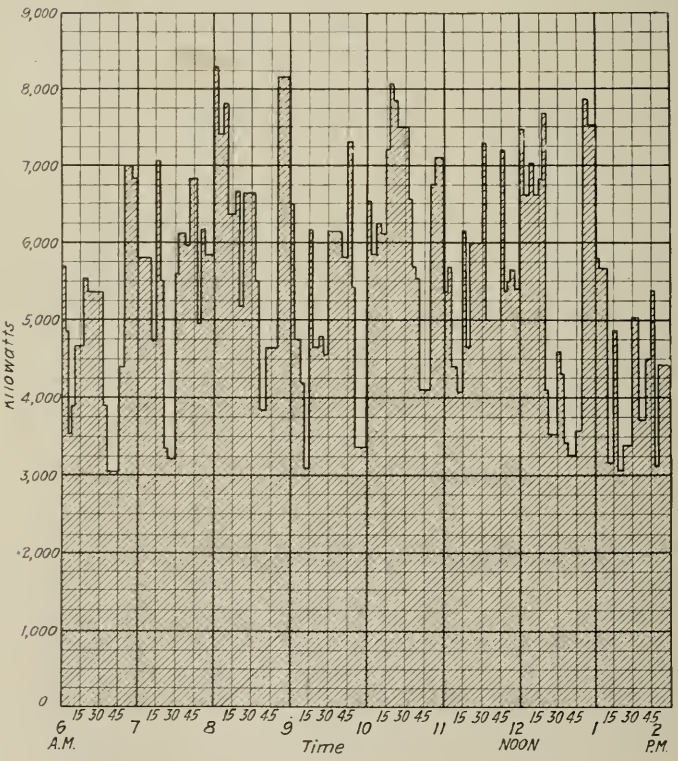


Fig. 146—Curve Showing Total Load Due to All Trains as Shown on the Train Sheet.

CHAPTER XXIX

AN ELECTRIFICATION PROBLEM—II

Important factors entering into an electrification problem are the amount of electric power that will be required to operate the electrified section and the location of substations. To determine the capacity of the power house required to provide for the handling of this service, or to know very closely the power requirements, or load, it is necessary to draw what is known as the "load curve". This curve shows the power required to operate trains of the weight specified and running on the schedule as covered by the train sheet; this sheet serves as a continuous representation of the power required.

The Load Curve.—To construct the load curve, reference is made to the train sheet, Fig. 143 and data Table VIII. With the few trains on this particular train sheet, it would easily be possible to plot the complete load diagram in one operation. However, with a large number of trains such a method would be extremely difficult; it is more convenient to plot first the power requirements for the trains running in one direction only, and then for the trains in the other direction. The sum of these two curves will give the total load demanded of the power house. Since this would be the best procedure to follow in a regular problem, in this assumed problem the load diagram for the trains running east will be plotted first.

The chart showing the load curve is laid out with "time" as the base and "kilowatts" as the ordinate—see Fig. 145.

Referring to the train sheet, Fig. 143, at 6 a.m., running east, there is a through freight on the 0.5 per cent grade, another on the level, and another running down the 0.1 per cent grade. Reference to Table VIII shows these trains to be

taking 2070 kw., 1110 kw. and 870 kw. respectively. The total kw. at 6 a.m. for trains running east is then 2070 + 1110 + 870 = 4050 kw. This total kw. is plotted on the load chart—Fig. 147. The load, for trains running east, will remain constant until one of the trains changes its rate of speed, stops, or encounters a different grade. In plotting the

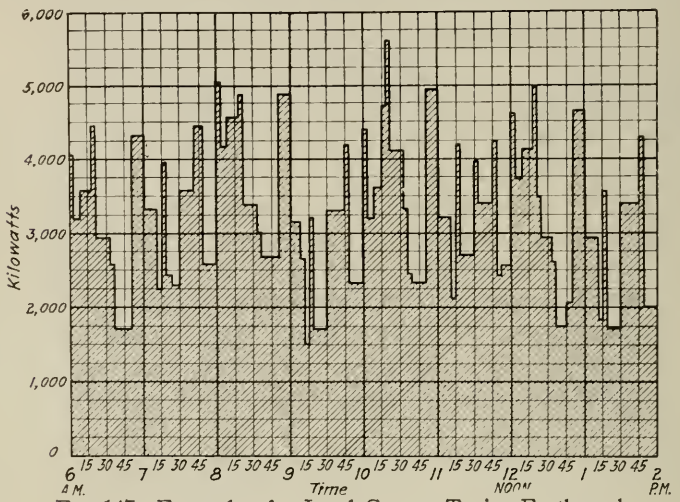


Fig. 147—Example of a Load Curve—Trains Eastbound.

"load chart" it will be found very useful to use a ruler on the train sheet—moving this ruler along with time as a base, and noting the exact time when a change takes place. Applying this suggestion to the train sheet, Fig. 143, it is found that the train operating down the 0.1 per cent grade stops at 6:03 a.m.; the other trains remain the same. The total kw. will then drop to 2070 + 1110 = 3180 kw. The next change that occurs is at 6:09 a.m. At this time the train operating on the level starts up the 0.2 per cent grade, and requires 1500 kw. instead of 1110 kw.—from Table VIII. The total will then be 3180 + 390 = 3570 kw., and will be constant until 6:18 a.m., at which time the train at Station D starts up, requiring 870 kw. additional. The total kw. will then be 4440 and will remain constant until 6:21 a.m. The train on the 0.2 per cent grade stops and reduces the kw. by 1500, leaving 2940

until 6:33 a.m. This method is carried out across the whole train sheet, and a load curve for eastbound trains is obtained, as shown in Fig. 147.

The same procedure is followed for the westbound trains, commencing at 6 a.m., and a load curve is obtained as shown by Fig. 145. The total load curve would be the sum of these two—the eastbound and westbound load curves—and is shown in Fig. 146.

A study of the load curve shows that the maximum load of 8300 kw. is at 8 a.m., and has a duration of three minutes. The next highest point, of longer duration, is 8150 kw. and exists from 8:51 to 9 a.m., or 9 minutes.

The maximum load demand of the power house would be greater than the maximum demand as shown on the load chart, as the losses have not been considered. The load diagram represents the actual load at the locomotives, and does not consider the losses due to transmission or in the substations; for safe calculation, a total efficiency of 80 per cent would be reasonable. The power house should, therefore, have sufficient capacity not only to supply the load required by the locomotives, but to provide for the losses as well. In this case, the maximum load of 8300 kw. would call for approximately 10,000 kw. as the total capacity which should be provided at the power house.

On this chart, the load diagram is particularly irregular; the kilowatt load may vary from one three-minute interval to the next by as much as 50 per cent. This variation, is excessive, but it must be borne in mind that the train sheet, from which the load chart was constructed, was based on assumed data, and only a few of the trains were shown; only enough to illustrate the method and not enough to cause confusion of lines; with more trains operating, the variations will be less, and the load curve much smoother. However, there will usually be variations in the load as the number of kilowatts taken by each unit hauling a train up the grade is of considerable magnitude. Conditions are different from those which exist on a large railway property where a large number of small car units are operating. In this latter case, the variations from minute to minute cannot be detected, as the change

due to any one unit is almost negligible as compared to the total load.

Substations.—In order to make these calculations complete, the location of substations for this electrification must be considered. The substations must be sufficient in number and capacity to handle the service as covered by the train sheet, and must be spaced so as to provide suitable voltage to the locomotives at all points along the line.

With a given load condition the voltage at the locomotives is dependent on the distance between substations and on the size of the copper trolley and feeder wires. The layout of the distribution system is an important factor and requires careful thought and study. The substations should be of such a number and so placed as to give the most economical distribution with the lowest capital outlay. If the substations are placed too far apart, and the feeders are too small, the interest on the capital cost for substations and the copper feeders will be low, but the cost of the power lost in the distribution will be high, so that the sum of the two may easily be greater than if more substations and heavier feeders had been installed. The sum of the interest on the capital cost, and the cost of power lost in distribution should be a minimum.

It is not the purpose of this chapter to go into great detail but simply to point out a procedure that can be applied to any electrification problem to obtain fairly accurate substation locations and feeder capacities.

Locating the Substations.—The problem of locating the substations can be considered in two different ways: Assume substation locations and determine the correct size of the trolley and feeder, or assume definite feeder sizes and then determine substation locations, to work with these feeders. These assumptions are not based on any definite location of the central power house; assume that power can be purchased at any location along the line, or that the power house is so located that transmission lines can be run to any point which may be desirable for the transmission of power at high voltage.

Consider the first method: For a trolley voltage of 3,000 volts direct current, the sub-stations can be placed from 30 to 35 miles apart and satisfactory voltage obtained with an

economical arrangement of feeders—this is the approximate distance between substations on the electrified section of the Chicago, Milwaukee & St. Paul. From experience gained in the layout and operation of electric railway systems, it has been found that the distance from the end substation to the end of the line should be approximately one-third of the distance between substations in order to get uniform voltage regulation; provided that the sizes of the trolley and feeder cables remain the same throughout the entire length of the line.

Size of Trolley and Feeders.—In addition to the voltage drop in the trolley wire and feeders—or in the third rail if such a system were under consideration—there is a "rail drop" on account of the running rails being used as a return circuit. The size of the track is determined by physical conditions, not electrical, so that it is only necessary to know the value of the resistance of the various sizes of rails, from which the voltage drop can be calculated and allowed for in determining the size which will be required for trolley wire and feeders.

The resistance of steel rails varies, depending upon the impurities in the iron; in general this resistance amounts to ten times that of an equal section of copper. Rails must be bonded at the joints and the use of these bonds adds a slight resistance to the track so that for general use a resistance of eleven times that of copper is taken. On this basis the volts-drop-per-mile per 100 amperes for a single track—100-lb. rails—is 2.5 volts. This value of 2.5 volts is known as the "unit drop"; it is very convenient to work out a problem using the "unit drop" rather than to figure resistances, etc., as will be seen from the following discussion:

Solution of Assumed Problem.—The railroad under consideration is single-track, 100 miles long; with substations 30 to 35 miles apart, there will be required at least three substations. If one substation is placed at the middle of the line and one at either side, thirty-five miles away, the distance from the nearest substation to the terminals A and E—see train sheet Fig. 143—would be 15 miles; with this spacing there would be satisfactory voltage regulation. Having definitely located the substations the problem is to determine the

size of the trolley wire and feeders. Generally the size of the trolley wire is determined by mechanical conditions and by the design of overhead construction so that the problem narrows down to the size of the feeder wires.

Maximum Load Condition.—The worst condition, as regards load and voltage drop, is when trains are bunched midway between two adjacent substations; reference to the train sheet will show this maximum condition. It will be noted that between stations B and N, from 11:20 a.m. to 12:00 noon, that there are four trains, two freight trains and two passenger. The train sheet was drawn to show the method of constructing it, and, to avoid complication and confusion, did not go into the detail of arranging the leaving time of trains, or the slowing-up of trains in certain sections, so as to have the trains meet at the sidings which exist along this single-track railroad. A convenient distance apart for sidings is five miles so that it easily is possible for the four trains to be bunched at two sidings five miles apart. Assume that there is

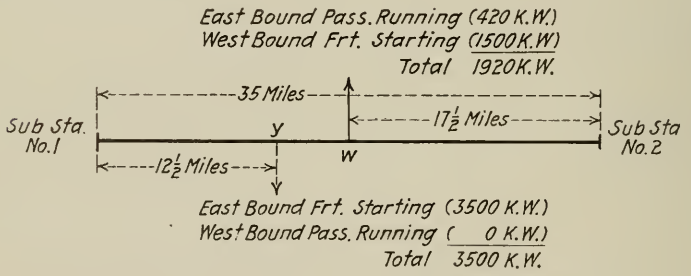


Fig. 148—Relative Location of Substations and Trains.

a siding 2½ miles west of station N and another siding 5 miles further west; the four trains will be bunched as follows: At the first siding a westbound freight starting and an eastbound passenger running—the freight train has pulled into the siding to allow the passenger train to pass. At the second siding an eastbound freight is starting and a westbound passenger running.

Location of Trains.—The relative location of the substations and the trains, as outlined in the preceding paragraph, is

shown graphically by Fig. 148. Referring to this graphic chart, the kilowatts (kw.) shown in brackets after each train is obtained by reference to Table VIII, "Data for Load Curve". The eastbound train at turnout, W, is running on the level and is taking 420 kw. from the line. The westbound freight is also on level track. According to the table, 1,100 kw. is required, but this value does not take into account the extra power required to accelerate the train when starting; the figure has, therefore, been increased to 1,500 kw. The eastbound freight train at turnout, Y, is located on a 1 per cent grade. Allowing for the necessary accelerating current there will be

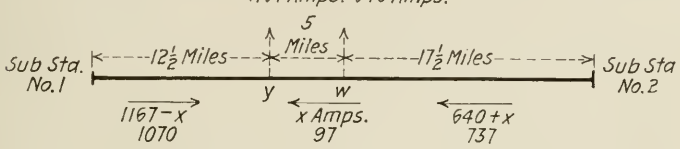


FIG. 149—Location of Sub-Stations and Points of Load in Terms of Amperes.

required 3,500 kw. The westbound passenger train is passing down the 1 per cent grade and therefore does not consume any power.

Summing up: 1,920 kw. will be required at turnout W, and 3,500 kw. at turnout, Y. With 3,000 volts on the trolley the respective currents in amperes will be:

$$\frac{1{,}920{,}000}{3{,}000} = 640 \text{ amperes},$$

and

$$\frac{3{,}500{,}000}{3{,}000} = 1{,}167 \text{ amperes}.$$

Direction of Current Path.—The next step is to determine how the current divides between the two substations. Fig. 149, shows graphically the substation locations and the points of load in terms of amperes. There are two trains at Y and two trains at W, but, assume for the moment, that there is only one load of 1,167 amperes at Y. Then with the same size trolley wire and feeder throughout, the current would divide between the two substations inversely as the distances of the

substations from Y. In order words, the current from substation No. 1 would be:—

$$\frac{22.5}{35} \text{ of } 1{,}167 \text{ or } 750 \text{ amperes}$$

and from substation No. 2 would be

$$\frac{12.5}{35} \text{ of } 1{,}167 \text{ or } 417 \text{ amperes.}$$

Returning to the problem: With 640 amperes taken off at W, assume that the current in the five-mile section would come from the substation shown as No. 2. Since the strength of this current is not known, it may be designated as X. The arrows show the direction of the flow of current. Assuming that the X-current is flowing from the No. 2 substation the other currents can also be expressed in terms of X. The current from substation No. 2 will be (640 + X) amperes, and the current from substation No. 1 will be (1,167 — X) amperes.

If the value of X can be determined, then the distribution of current between the two substations can also be determined. Since two different voltages cannot exist at Y, at the same time, voltage drops from either substation to point Y are the same when each substation is operating at the same bus bar voltage. With uniform arrangement of track and feeder the resistance, per mile, of the trolley wire and feeder and track will be the same, so that for determining the value of X, distances can be used instead of resistances. The voltage drop, then, from substation No. 1 to Y is proportional to 12½ (1,167 — X)—miles × amperes—and the voltage drop from substation No. 2 is 17½ (640 + X) + 5 X. These two voltage drops must be equal, therefore 12½ (1,167 — X) = 17½ (640 + X) + 5 X, and

$$14587.5 - 12.5\,X = 11200 + 17.5\,X + 5\,X$$
$$35\,X = 3387.5$$
$$X = 96.8 \text{ amperes}$$

or for practical use, X = 97 amperes.

The assumption as to the flow of current in the five-mile section was correct. However, if the assumption was incorrect it would not seriously affect the solution of the problem;

in this case the value would come out as negative and would indicate that the assumption was incorrect and it could be changed accordingly. To illustrate how this would affect the working out of the problem, assume that the current, X, was flowing opposite to that shown in Fig. 149. Then:

$$12\tfrac{1}{2}\,(1167 + X) + 5\,X = 17\tfrac{1}{2}\,(640 - X)$$
$$14587.5 + 12.5\,X + 5\,X = 11200 - 17\tfrac{1}{2}\,X$$
$$35\,X = -3387.5$$
$$X = -97 \text{ amperes.}$$

The negative sign shows that 97 amperes are flowing opposite to the last assumption in the direction originally assumed.

Determining Size of Feeders.—In order to determine the size of the feeder, it is necessary to choose a maximum voltage drop. The greater the maximum allowable drop the smaller can be the copper section and the less the drop, the larger must be the copper section. With a 3000-volt direct-current electrification, as has been assumed, a maximum drop of 900 volts would give satisfactory operation. Taking advantage of the allowable drop of 900 volts it would mean that the drop from substation No. 1 to point Y, can be 900 volts. The total drop is made up of the drop in the rails and the drop in the feeders and trolley wire.

A convenient method is to work out the problem on the "unit drop" basis—voltage drop per mile per 100 amperes. The unit drop of the trolley and feeder, and track, on the basis of 900 volts allowable drop from substation No. 1 to point Y is:—

$$\frac{900 \text{ (volts)}}{12.5 \text{ (miles)} \times 10.7 \text{ (hundred amps.)}} = 6.73 \text{ volts drop per mile per 100 amp.}$$

As previously mentioned the "unit drop" for a single track of 100-lb. rails is 2.5 volts. Subtracting this drop from the total unit drop of 6.73 volts we have 4.23 volts unit drop for the trolley and feeder. The unit drop for a one million circular mil cable is 5.54 so that to obtain only 4.23 volts unit drop, the required circular mils will have to be

$$\frac{5.54}{4.23} \times 1{,}000{,}000 = 1{,}310{,}000 \text{ cm.}$$

A trolley construction similar to that in use on the Chicago, Milwaukee and St. Paul electrification, which is equivalent

to two No. 0000 copper wires, is satisfactory, and this type of construction will be assumed in this problem. The circular mils for two No. 0000 wires is 423,200. Subtracting this value from the 1,310,000 cm, required we get a figure of 886,800 cm. which is the size of feeder necessary to give the voltage regulation desired.

The method outlined is such that with modifications it can be applied to any problem and it hardly seems necessary to go into any further detail.

CHAPTER XXX

ELECTRIFICATION SYSTEM OF THE FUTURE. COST OF OPERATION.

American industrial life is largely dependent upon the railroads. Sections removed from the seacoast must depend chiefly upon land transportation as there is relatively little water transportation compared to the whole tonnage moved. The waterways connect only a few of the centers of population, so that the very industrial existence of the United States of to-day depends upon the condition of the railroads, and in the future on their capacity to handle the ever increasing volume of traffic. Inevitably the tonnage will continue to increase with the increase in population and the growth of the industries; agricultural and manufactured products will increase in volume, producing traffic demands at an ever increasing rate.

The object in briefly mentioning this question is to bring before the reader the fundamental thought that the capacity of many of the railroads must be increased; that serious question arises as to the adequacy of the present means of transportation and that a vast increase in capacity over that of the present steam operation must be provided. To accomplish this, what is more promising than electricity? We have seen what electrification has accomplished in other industrial problems, and who can now say what may not be accomplished in the application of electricity to the railroads in the future. Electricity has revolutionized many industries and results in the handling of heavy train loads at high speeds, which can now hardly be visualized, may be expected.

Electricity will assuredly be the power for general use in the future and many may ask what will be the system used. Today there are electric locomotives of 300 tons weight oper-

ating over sections of continuous line of 440 miles; there are heavy traction electrifications with power supplied from a third-rail to the locomotives at 600 volts direct current (D. C.); and from a trolley at 1200 volts D. C.; 2400 volts D. C.; 3000 volts D. C.; 3300 volts alternating current (A. C.); 6600 volts A. C. and 11,000 volts A. C. What system is going to predominate in the future? To determine this, we must look further than present day conditions and must realize that the ton-miles per year handled by the railroads will increase rapidly; that the electrification system installed must necessarily not be one that will handle the present day requirements alone, but one that will be capable of handling, over the same rails twice, or even four times the volume of traffic that is being handled today. This means that the distribution system used must be capable of delivering heavy drafts of power at remote distances from the source of generation, for the intensive operation of any railroad means heavy trains running at high speeds, requiring enormous drafts of power. The system must be one that can properly handle the maximum transportation requirements that it is desirable to impose upon it.

At present the limit in the United States for the alternating current system is 11,000 volts, but there is no reason why this should not be increased as demands are made for heavier drafts of power, while with increase of the direct current voltage, the motors must also be designed to operate on higher voltages and therefore a limit is soon reached. With the alternating current system the trolley voltage can be of any value to give ideal transmission of the power demanded, without affecting the design of the motors, for high voltage can be reduced to any desired amount by the use of the transformer.

A study of the great and rapid progress made by the power companies, shows conclusively that the great expansion in the use of the electric current generated by these large power companies has been due chiefly to the transmitting of the power at higher and higher voltages with smaller and smaller currents required for the same horsepower on energy transmitted.

So it can be with the electrification of railroads. Enormous

drafts of power will be required to handle trains of 7000 to 8000 tons up a 1 per cent grade at 20 miles an hour—a transportation feat which is not so impracticable as it may now appear—and voltages must be raised to meet these demands with a minimum amount of current. It is an established fact that the cost of railroad electrification will be largely influenced by the amount of current used, therefore high voltages are necessary for economical electrification, and this would indicate the necessity for the adoption of the alternating current system.

Cost of Electric Locomotive Operation.—An important feature affecting future extension of railroad electrification is the cost of the electric locomotive, how the cost of operation compares with steam operation and on what basis different types of locomotives, and how locomotives operating on various different railoads, compare as to maintenance costs.

The first cost of an electric locomotive capable of a certain draw-bar pull is about double the cost of a steam locomotive of equal power. At first thought this fact seems to be a handicap, but it must not be forgotten that the electric locomotive is available for service at all times, that it can run hour after hour if kept within the capacity for which it was designed, and that theoretically, one electric locomotive will replace two steam locomotives. Moreover, in some cases, in equal service and operating on the same basis, the operating cost per mile of the electric locomotive has been shown to be about one-half that of the steam locomotive. The electric locomotive, however, will operate many more miles each day, and on this acount, will be subjected to more wear and tear, so that costs based on the locomotive-mile may be misleading. Especially is it very misleading if comparison is to be made with another type of locomotive which is operating on a different railroad or over a different division where conditions may be widely different.

The locomotive-mile, as can readily be seen does not take into account the profile over which the locomotive is operated; nor the schedule speed maintained; or the size of the locomotive; or the tons hauled. Naturally a heavy locomotive

will cost more to maintain than a light one and the weight of the loads hauled will be a factor.

The costs may also be computed on the ton-mile basis. This comparison is better than the locomotive-mile basis but still does not cover the situation completely; the profile has not been considered. While a ton-mile is a ton-mile under all conditions, considerable more power is required to move a ton up a grade than on the level, with a resulting greater wear and tear and higher maintenance costs. Starting and stopping of the train on a grade also imposes greater stresses on all parts and increases the heating of the electrical equipment.

It is generally agreed that the maintenance costs will vary in some direct ratio with the actual work done by the locomotive—horsepower expended. In view of this fact, not only are the two methods described not complete, but they are still more inaccurate because of the fact that the mileage which is credited to the locomotive is not accurate on account of the difficulty in knowing, all of the switching, dead, or light service mileage. The ton-mile record is equally inaccurate.

The most accurate basis for comparison is the cost of maintenance per unit of power used by the locomotive. In the case of the electric locomotive this unit of power is very easily obtainable. The unit is the kilowatt-hour and can be obtained by installing an electrical instrument, known as an integrating wattmeter, on the locomotive to measure the kilowatts of power taken from the third-rail or overhead trolley wire. The horsepower required will vary with the grade, stops, and load, so that the kilowatt-hour input will also vary; by measuring this input the total work done by the locomotive is known. The kilowatt-hour measurement will include all movements, whether light, loaded, or switching, and the true working conditions are then known. With the computing of maintenance costs based on the kilowatt-hour input, there would not be the great difference in costs per locomotive mile as appears to exist for different locomotives on different railroads. It would then be possible to make a satisfactory comparison of the costs and to analyze the merits of the different locomotives for the service required.

APPENDIX

RAILROAD ELECTRIFICATION

The development of electrification projects on many of the steam railroads of the United States forms an important step in the solving of transportation problems. In many localities, due to topographical conditions, the maximum of service obtainable from steam locomotive operation had been reached; the electrification of such sections has resulted in not only relieving the congestion of traffic, but has also provided capacity for the movement of increased tonnage over the same trackage.

A brief outline of the development of these electrifications in America as well as much valuable data in tabular form on the electrification of many railroads throughout the world follows:

Baltimore & Ohio—Baltimore Tunnels.—Three general types of electric locomotives have been used on the Baltimore & Ohio in the tunnels at Baltimore. The first two, being pioneers in service on steam railroads, are of interest only from a historical point of view. The class LE-2 locomotives are still in operation, although they are of a design that would now be considered obsolete and is not being used in new construction. An interesting feature with respect to these locomotives is that they are handling the maximum tonnage freight trains operated over the division, notwithstanding the fact that during the period they have been in service, the steam motive power has twice been replaced with heavier equipment in order to secure greater capacity. This has been possible because of the flexibility of multiple-unit control; when they were first built they were operated in two-unit

combinations, while now they are run as a three-unit combination, thus providing a 50 per cent increase in capacity.

Other electric locomotives built in 1910 and 1912 are of the Detroit Tunnel type and might be considered as standard for the present Baltimore & Ohio electrification. This later design has been found to be very satisfactory for limited zone, moderate speed service, as they are practically equally well adapted for passenger, freight and switching service.

The current collecting system was originally of the overhead type but in 1902 it was replaced by the third-rail system.

Boston & Maine—Hoosac Tunnel.—The Hoosac Tunnel electrification, extending for a distance of 7.9 miles east of North Adams, Massachusetts, and embracing 4.75 miles of double track tunnel, was undertaken primarily to increase the capacity of the tunnel and to make train operation more safe through the elimination of the use of steam locomotives. Electric operation was begun in 1911.

The original electrical equipment comprised five alternating-current locomotives of the 2-4-4-2 type developing 51,000 lb. tractive effort as a maximum—20,500 lb. continuously—and working under a trolley pressure of 11,000 volts. Two locomotives of similar characteristics were added in 1917. These locomotives handle 1,750 tons behind the steam locomotive, this being the maximum tonnage assigned for steam operation with one locomotive over this section.

For several years prior to the electrification of the tunnel the freight business on the division was handled largely with locomotives developing a tractive effort of 33,000 lb., the train loads being limited to 1300 tons eastbound and 825 tons westbound, these limits being fixed by grades which existed at other points on the division. While the grade in the tunnel was but 26.4 feet to the mile, the rail conditions were exceedingly bad and so much difficulty was experienced in making the run that helper engines were provided for many trains in both directions. The size of these helpers was gradually increased from those developing 25,000 lb. tractive effort, in use in 1895, to oil-burning Mallets of 66,000 lb. tractive effort, used in 1910. With the advent of electric operation, the four Mallet locomotives which made up this particular equipment were diverted to other uses and electric helping loco-

motives were provided for all trains, both passenger and freight.

The current collecting system is of overhead construction of the single catenary type; copper being used for a messenger in the tunnel, with fittings of bronze to withstand more successfully the corrosive effect of the gases from the steam locomotives, some of which still pass through the tunnel, and the action of solutions percolating through the tunnel roof.

Butte, Anaconda & Pacific.—The Butte, Anaconda & Pacific Railway was built in the year 1892, principally for transfer service between the ore mines in Butte and the Washoe Smelter at Anaconda. The track connecting these two cities are approximately twenty-six miles long, but the yards and sidings bring the total mileage up to 120.

Work on electrification began in the spring of 1912 and the first electric locomotive was run experimentally at Anaconda on May 4, 1913. Two weeks later a double-unit electric locomotive began on the Smelter Hill line to haul the ore between the East Anaconda yards, where the trains are broken up into "drags" for distribution, and the Concentrator yards, the distance being about 7 miles.

Regular passenger service between Anaconda and Butte, a distance of 25.7 miles, was placed in electrical operation in October, 1913.

In October, 1913, a double-unit electric locomotive was put in the day freight service between East Anaconda and Rocker, a distance of 20.1 miles. The remainder of this class of freight service was gradually taken over during the months of October and November, 1913.

Erie Railroad.—A change from steam to electric motive power was made on a portion of the Rochester division of the Erie Railroad, in June, 1907. This installation bears the distinction of being the first case where a single-phase alternating-current system has been placed in commercial operation on a steam railroad.

The electrified section extends from Rochester, N. Y. to Mount Morris, N. Y.—a distance of 34 miles. The electric service is devoted solely to passenger traffic; the freight service continues to be handled exclusively by steam.

The rolling stock consists of eight 52-ton passenger cars

each equipped with four 100-h.p. motors. The gear ratio is 20:63; the wheel diameter, 36 in.; and the cars are supplied with multiple-unit a. c. control and automatic air brakes.

Power is purchased from the Ontario Power Company. It is received at 60,000 volts, 3-phase, 25 cycles. The voltage at the overhead trolley is 11,000. One substation, located at Avon, N. Y., is used and is equipped with three 750 k. v. a., 60,000 - 11,000-volt O. I. W. C. transformers.

Chicago, Milwaukee & St. Paul.—The Chicago, Milwaukee & St. Paul was first interested in electrification in the section through the Bitter Root Mountains, and the reason for its consideration was to lessen the fire hazard, as the line was through a very extensive and important forest reserve of the United States Government.

In their operations to secure terminal facilities at Butte and to secure traffic for their road, the Chicago, Milwaukee & St. Paul established relations with the Amalgamated Copper interest in Montana and acquired a substantial interest in the Butte, Anaconda & Pacific Railroad, which was owned by the Amalgamated Company.

The electrification was effected by high-voltage, direct-current, the same as the Butte, Anaconda & Pacific. The analysis of the probable load conditions with 2,500 ton trains led to the conclusion that a voltage higher than 2,400 was economical and desirable and should be made available.

A demonstration of a high-voltage car equipment which was operated at 6,000 volts, direct current, led to the decision that 3,000 volts would be the desirable nominal operating voltage.

Work was commenced in 1914 and completed in 1917, giving a continuous main line electrification of 438 miles from Harlowton, Mont., westward to Avery, Ida. Near the center of this section is Deer Lodge; the east end is called the Rocky Mountain Division, the west end, the Missoula Division.

Westward from Harlowton, the first mountain range encountered is the Big Belt Mountains, on which the railroad reaches an elevation of 5788 ft. above sea level. The next range is the Rocky Mountains, which are crosed at an elevation of 6322 ft. On the Missoula Division are encountered the Bitter Root Mountains, the maximum elevation reached be-

ing 4163 ft. For 21 miles on the eastern slope of the Rocky Mountains the maximum grade is encountered, which is 2 per cent. The maximum curvature in the electrified zone is 10 deg.

In addition to the electrification of the Rocky Mountain and Missoula Divisions, the railroad began, in March, 1917, the electrification of an additional 207 miles of main line on the Columbia and Coast Divisions extending from Othello to Tacoma, Washington, and to Black River, nine and one-half miles south of Seattle, across the Saddle Mountains just west of the Columbia River and the Cascade Mountains.

The general character of the electrical layout is similar to that used in Montana and Idaho, except as noted below:

Locomotives for passenger service are of the bi-polar type, having a total weight of approximately 265 tons and capacity sufficient to haul over the road profile at a speed of approximately 25 miles per hour, a twelve-car passenger train weighing 960 tons. Locomotives for freight service were provided by changing the gear ratio of the older passenger locomotives used on the Rocky Mountain and Missoula Divisions, and in place of the latter locomotives there were used for the Rocky Mountain and Missoula Divisions ten quill-type locomotives having approximately the same weight and capacity as the bi-polar motors.

All the main line locomotives are provided with apparatus and connections for allowing of regeneration on down grades. The motors then act as separately excited generators and furnishing current to the trolley system, this current flowing directly over the trolley wires to other locomotives which are motoring, or flowing back through the adjacent sub-stations and eventually into the high-tension transmission line to other substations, or into the power company's system.

The trolley is overhead construction of the catenary type, supported by brackets on poles except at some curves where span construction is used, and in tunnels where the wires are attached to steel channels suspended from the tunnel roof.

Power is supplied over the two transmission lines, one running from the Long Lake plant of the Washington Water Power Company to the Taunton substation; the other from the Snoqualmie plant of the Puget Sound Traction, Light &

Power Company to Cedar Falls and Renton substations, these lines connecting at the sub-stations mentioned with the railroad's high tension tie-line.

Grand Trunk—St. Clair Tunnel.—Electric operation of the St. Clair Tunnel of the Grand Trunk Railway dates from early in 1908 when five locomotives were put into service. The characteristics of the tunnel and other operating requirements necessitate the haulage of 1000-ton trains up a two per cent grade one mile long. The single catenary system is used for the line construction at the terminals and approaches to the tunnel. For use inside the tunnel an ingenious modification of the catenary construction is used, which employs two parallel 7/16-inch messenger cables and two 4/0 trolley wires. The double messengers are suspended at intervals of twelve feet on barrel type insulators. and the trolley wires are hung from the messengers at points between the barrel insulators by means of insulated hangers.

Actual tests have shown that a single locomotive unit is capable of exerting a tractive effort of 45,000 lb. on a clean, dry rail. If it should become necessary to stop on the 2% grade, the electric locomotives can start and accelerate the train up to full speed, which is about 11 m.p.h. on this grade.

Great Northern—Cascade Tunnel.—The electrification of the Cascade Tunnel of the Great Northern Railway was completed and put in operation in 1909.

The locomotives used in this service weigh 115 tons each. All driving wheels are traction wheels, each motor being coupled to its axle in identically the same manner as is done with street-car motors, being geared in single threads. An interesting feature is that there are no cushion springs in the gear to equalize the tooth pressure, as has been considered necessary on almost all heavy locomotives; it has been found there is an equal amount of wear on both pinions, the tooth pressures seem to be uniform, and the wear has been almost negligible on all of these gears and pinions.

The current is conducted into the locomotive by two trolley poles and wheels located at each end of the locomotive. The speed of the driving motors is constant, being of the induction type, and drives the locomotive at a constant speed of 15 miles per hour. The reason this constant speed was adopted was

that this was supposed to be a link in a larger system in which the principle of regeneration on descending grades is very desirable, and it was, at the time, the only method of regeneration which had been developed. The results of this regeneration were such that this feature was shown to be very desirable for all electrification, especially on mountain grades. Since that time the regenerating locomotive, using the series direct-current motor, has been developed.

Long Island Railroad.—The Long Island Railroad is essentially a passenger-carrying line, serving suburbs of N. Y. City and a also heavy excursion travel to the seashore of Long Island.

A network of lines of the company covers the western end of the island within 30 miles of New York City and delivers heavy commuter and excursion travel to the New York and Brooklyn terminals.

In the beginning, the electrification was undertaken in connection with the "Atlantic Avenue Improvement" which required "smokeless" operation through a new tunnel line into the central part of the Borough of Brooklyn, with a new underground passenger terminal at Flatbush Avenue.

The first lines electrified, and which were completed in 1905, comprised the Atlantic Avenue Division between Flatbush Terminal and Belmont Park (Queens) and the Rockaway Beach Division between Woodhaven Junction and Rockaway Park, and to Valley Stream via Far Rockaway—a total of 38.1 route miles.

In May, 1908, the line from Queens to Hempstead and Mineola, 9.5 miles, was equipped with third-rail. In June, 1910, the line from Jamaica to Woodside, Long Island City, 6.3 miles, and from Glendale to Ozone Park, 4.5 miles, was electrified. In September of the same year the line from Woodside to the Pennsylvania Station, New York City, 5.1 miles, was completed. The line between Valley Stream and Long Beach, 6.8 miles, was also equipped with third-rail.

This gave an all-electric run from both Flatbush Terminal and Pennsylvania Station to Hempstead and Mineola, and to the beach resorts.

In October, 1912, the North Shore Division from Winfield Junction to Whitestone Landing, a distance of 8.3 miles, was

electrified and a year later the entire division to Port Washington, a distance of 10.5 miles, was included. These extensions since 1905 have increased the electrified route miles to 89 and the total main line electric trackage to 187.5 miles.

Steam operated express trains to the eastern end of Long Island are taken from the Pennsylvania Station by electric locomotives to Harold avenue, Long Island City, at which point steam locomotives are attached. It is probable that in the near future electric locomotives will haul these through trains to Jamaica, which is a central point for the various lines. The freight service is conducted by steam power and on some portions of the electrified system steam locomotives are used to operate both freight and through passenger trains.

The third-rail, a. c. d. c. system is used with 650 volts d. c. on the third rail and three-phase, 25-cycle at 11,000 volts on the transmission lines.

The power is obtained from the Pennsylvania Railroad power house located at Long Island City and is delivered to the Long Island Railroad transmission lines at 11,000 volts.

With the exception of the thickly populated sections of Brooklyn and Queens, where underground cables are used, and the submarine cable at Broad Channel and Beach Channel, the overhead type of construction is used to distribute the high tension alternating current to the converter stations.

New York Central—New York to Harmon.—The electrification of the New York Central in and near New York City was started because of the action of the New York State Legislature in 1903, forbidding the use of steam locomotives south of the Harlem River after July 1, 1908. This action was taken because the steam and smoke of the steam locomotives so filled the two-mile Park Avenue tunnel just north of the terminal that it was extremely difficult, frequently impossible, to determine the location of trains.

This operation was begun with both electric locomotives, multiple-unit cars, and trailer cars, some of which were subsequently equipped with motors.

A direct current system, rather than alternating current, was adopted because at the time there had not been sufficient practical experience with the alternating current for a trunk line problem requiring the highest possible reliability of ser-

vice. Restricted overhead clearance in the Park Avenue tunnel, which prevented the use of overhead conductors, and also legal obstacles to the use of high voltage overhead trolley lines within New York City were other factors.

The operating service obtained from the electric equipment has been more reliable, with fewer delays, than was obtained from the steam locomotives which were displaced.

The electric locomotives have bipolar gearless motors. The under-running type of third-rail is used and is of decided advantage in case of heavy snowfall which, with the over-running type of third-rail, considerably hampers and very often prevents the collection of power resulting in unsatisfactory train operation.

Because of the very great importance of reliable service two power plants were built, each with a capacity sufficient to furnish current for the entire electrified zone. Duplicate transmission lines were carried over the territory most essential, and storage batteries with sufficient capacity to operate the electric division for a short period which experience on other electrified railroads had shown might occur.

New York, New Haven & Hartford.—Electric operation was started on the New York, New Haven & Hartford, in June, 1908, as far as Stamford, Conn., 36 miles from the Grand Central Terminal; in 1914 it was extended to New Haven, 72 miles from the Grand Central Terminal.

The electric rolling equipment consists of both electric locomotives and multiple-unit cars; all operate at 11,000 volts, single-phase, alternating current. Some of the equipment is also arranged to operate at 660 volts direct current, in order to permit Long Island Railway trains to enter New York City over New York Central or Pennsylvania tracks.

Although the New Haven equipment was designed at a time when data on the requirements of an alternating current, high voltage, high speed, heavy train capacity locomotive was very meager, these locomotives today compare favorably with those designed after all the experience gained in the last thirteen years. In general design the locomotives built in 1919 are the same as some of those built in 1910, most of the principal improvements of the 1919 machines being in the auxiliary apparatus and the control apparatus. The electric locomotives

used on the New Haven may be divided into two groups—the standard types, and the experimental types:

STANDARD

		Wheel arrangement
1—Gearless motors for fast passnger service. First type built. Now obsolete for single-phase operation.....	01-041	2-4-4-2
	Frt. 076-0111	2-4-4-2
	Sw. 0200-0214	0-4-4-0
2—Geared passenger, freight and switcher locomotive....	Pass. 0300-0304	2-6-2-2-6-2

EXPERIMENTAL

		Wheel arrangement
Geared 3-truck fast freight or passenger locomotive.....	069	2-4-4-2
Geared 2-truck fast freight or passenger locomotive.....	071-2	2-4-4-2
Geared side rod freight locomotive.....	068	4-4-4-4
Side rod locomotive	070	2-4-4-2

These locomotives represent every mechanical type of drive put forth to date, either in America or in Europe, as the best solution for translating the torque of the motors to tractive effort at the rim of the driving wheels. The type that proved best for passenger and freight service is represented by New Haven locomotives 076-0111 and 0300-0304; this is a geared type with twin motors. Although the gearless locomotive of the 2-4-4-2 type (01-041) has given very good service for the past twelve years in both local and fast express service, it is now replaced by the geared locomotive of 0300-0304 type. The other "experimental" types have not proved successful.

The type represented by locomotive 068, with a geared side rod drive and a 4-4-4-4 wheel arrangement, has been used for polyphase motor drive to obtain certain advantages possible with such a combination, but not available with single-phase commutator motors. The side rod type, represented by locomotive 070, wheel arrangement 2-4-4-2, has not proved successful on the N. Y., N. H. & H.

All New Haven locomotives and cars collect current from an overhead trolley wire by a sliding pantagraph trolley. A third-rail shoe is also provided, for operation over the New York Central and Pennsylvania Railroads into New York City. The necessity of operating at both 11,000 volts alternating current and 660 volts direct current complicates the locomo-

tives to some extent as well as requiring some additional apparatus which otherwise would not be needed.

New York, Westchester & Boston.—This road affords an example of electric suburban service under steam operating conditions. The main line has four tracks and extends for a distance of 6.8 miles from Westchester Ave. in New York City, to Mt. Vernon, N. Y., where it is divided into two double-track branches, one running 2 miles to New Rochelle, and one 9.4 miles to White Plains, N. Y. The main line connects with the Harlem River Division of the New Haven system, the tracks of which are used for three miles to the Harlem River Station.

Trains normally consist of single cars in local service, but multiple-unit train operation is used to handle the heavy traffic during rush hours. Each motor car is equipped with two Westinghouse 170 h.p. single-phase motors, and unit-switch control.

Norfolk & Western.—The Norfolk & Western electrification is on a portion of the Pocahontas Division—known as the Elkhorn grade in West Virginia.

The construction was started in 1913 and the electric locomotive operation in 1915. The capacity of the electric equipment, as installed, could handle an average of about 65,000 tons per day, in addition to handling the through freight trains by electric pusher locomotives and the passenger trains with their steam locomotives by attaching electric locomotives. In the latter case the necessity for an electric helper occurs only where the trains are so heavy as to require doubleheading on the grade. It was customary under steam operation to make up the train to a maximum weight of 3,250 tons behind the engine and to handle it by a Mallet road engine and a Mallet helper over the division, and, in addition, a Mallet pusher up the 1.5 per cent and 2 per cent grades, or three engines per train. In cold weather and under adverse conditions the trains were reduced to about 2,900 tons. Tonnage trains were handled normally at speeds of seven or eight miles per hour on the grades, but on account of the ventilating conditions the speed was reduced to six miles per hour in the Elkhorn tunnel.

Because of the slow speed necessary in this tunnel, and also because of the fact that it is of single track, a serious restric-

tion in the capacity of the line occurs at this point and has occasioned frequent congestion and delay. Generally, however, the division is double track throughout, with frequent long passing sidings, making it in part a three-track line. As an electrified third-rail along the tracks was not practicable under the local conditions, an overhead collector was required. The single-phase alternating current system was adopted.

A feature of this installation is the adoption of three-phase motors on the locomotives in connection with single-phase current delivered to the locomotives. The required three-phase current for the motors is produced by a "phase-converter," which is a simple self-contained piece of apparatus. The three-phase motor used for driving the locomotive has, however, a considerable speed characteristic which is not desirable in some kinds of railroad operation, but for this particular service has important advantages in respect to maintaining certain predetermined and limited train speeds irrespective of the loads. Furthermore, this type of motor has the valuable characteristic of automatically returning regenerated current to the line on the down grades, this being effected without additional machinery or complication when the predetermined running speed is slightly exceeded during the coasting period. This characteristic may, at times, result in a considerable saving of power as the regenerated current is available for use in assisting to propel other trains which are in movement on the division, but its most valuable feature is that of "dynamic braking," or controlling the train on down grades without the use of air brakes.

Pennsylvania Railroad.—Electrification operations began on the Pennsylvania Railroad with the electrifying of that portion of the system between Camden and Atlantic City, New Jersey, and known as the West Jersey and Seashore.

The power house for supplying this installation is at Big Timber Creek, just north of Westville, six miles from the Camden terminal. There are eight substations, one at Westville, one at each of the terminals in South Camden, Clayville and Atlantic City, and four at intermediate stations. The transmission line, 71 miles long, is double throughout.

The electrification of the New York Extension of the Penn-

sylvania Railroad is one of the most stupendous tunnel and terminal electrifications in the world. Thirty-one electric locomotives, each equipped with two Westinghouse 2,000 h.p. motors, have handled all the passenger trains in and out of the New York Terminal for the past eleven years. These locomotives have a one year's record of 55 minutes delay to trains for all causes due to motive power failure. and from November, 1910, to November, 1918, the locomotives made a total mileage of 9,508,765 miles, during which time they had a total of only 21 engine failures—an average of 78,584 miles per locomotive detention during eight years of service.

The locomotives incorporate many novel features in electric locomotive design. The starting requirements are unusually severe; the requirement being to start a train of 550 tons trailing load upon the tunnel grades under the river which are approximately two per cent. The guaranteed tractive effort of 60,000 lb. is amply within the capacity of the electrical equipment. The normal speed, with load, upon a level track is 60 miles an hour, but the locomotive is capable of speed much in excess of this.

The Philadelphia-Paoli electrification of the Pennsylvania at the Broad Street Terminal in Philadelphia, is an example of efficient terminal operation. This terminal had reached its capacity with steam operation in 1915 and conditions were becoming intolerable because of the greatly increased traffic. Due to the location of the terminal, it was considered impossible to enlarge it, so electrification was suggested. The terminal was subsequently electrified for suburban service and it was soon apparent that this would not only give the necessary relief, but would also take care of a large increase of traffic which time would bring about.

Multiple-unit trains are now handled in and out of the Broad Street Terminal much more expeditiously than they were with steam motive power. The time required to bring a train into the station and out again, including unloading of passengers and loading the train again, has been cut to about one-third of that required under steam operation.

There are at present nearly 600 trains daily arriving and departing from this station, approximately one-third of them being propelled by electricity. Fifty trains pass over the

six tracks at the switch tower between the hours of 5 and 6 p. m. and at one time during this hour seventeen trains are dispatched past this tower in as many minutes—a remarkable performance when it is considered that the station was originally designed to accommodate only 160 trains a day.

The electrification includes the main line suburban service to Paoli, 20 miles west, and the Chestnut Hill branch of 12 miles. The combined car mileage of the two lines for one month has been as high as 252,216, with five detentions totalling 14 minutes. In one year the cars have averaged 235,994 car miles per month with an average of forty-five detentions, and a total average a month of 25.4 minutes.

Southern Pacific—Oakland, Alameda and Berkeley Suburban Lines.—Electric operation of the Oakland, Alameda and Berkeley Suburban Lines of the Southern Pacific was begun in 1911. Trains of from one to seven cars are operated by the Sprague multiple-unit system, a train unit consisting of one motor and one trailer car, the motor car carrying four 140 h.p. motors. The two motors on each truck are connected permanently in series, so that, although the equipment is a four-motor equipment, the control is of the two-motor type.

The power for this service is generated in the Fruitvale Power Station; this station furnishes 25-cycle current at 13,200 volts, which is transmitted to three sub-stations, one of which is located in the power house, the other two at West Oakland and Berkeley, respectively. The 13,200-volt distribution is in duplicate three-phase circuits, one of which runs from the power house to West Oakland substation through Oakland, the other between the same points through Alameda, the circuit being split as a protection against interruptions by reason of fire in the manufacturing districts of Oakland, through which the circuit is run. One double three-phase circuit distributes from West Oakland to Berkeley substation. The total single trackage electrified is about 100 miles.

TABLE A

ELECTRIC OPERATING DATA OF THE PRINCIPAL AMERICAN RAILROADS

Name of Road	Mileage of road	Mileage of single track	Total Kw-hr. per year	Number of locomotives			Aggregate wt. of locos. pass. frt. switch.	Multiple unit cars		Gross ton miles per year (trailing)		Locomotive miles per year	
				Pass.	Frt.	Switch.		No.	Av. wt.	Passenger	Freight	Passenger	Freight
							Tons		*Tons*				
Baltimore & Ohio R. R.	3.6	7.96	5,628,690	4	4	0	720	0	.....	.....	.....	†232,735	
Boston & Maine R. R.	7.92	23.80	7,250,640	†7	... ..	.....	916	0	.. ..	18,424,000	158,053,000	36,440	113,502
Butte, Anaconda & Pacific	28.00	90.50	18,749,189	2	26	. .....	2,240	0	.....	13,879,260	200,149,124	83,524	609,280
Chicago, Milwaukee & St. Paul	646.70	860.40	¶160,932,232	15	42	5	16,519	0	.....	599,516,000	2,901,500,000	920,568	1,900,564
Erie R. R.	34.00	40.00	2,042,843	.....	.....	.....	.... .	8	52	24,641,408	.....	.....	.....
Grand Trunk Ry.	4.00	12.00	4,103,476	†6	.....	.....	796	0	.....	4,280,156	35,507,215	10,746	180,594
Great Northern R. R.	4.70	6.50	3,003,700	†4	.....	.....	460	0	.....	3,800,000	8,411,067	26,424	46,320
Long Island R. R.	*85.69	227.08	105,450,000	0	1	0	90	634	46	1,073,388,277	.....	.....	27,499
Michigan Central R. R.	4.60	26.40	8,246,560	†10	.....	.....	1,080	0	. ....	14,067,000	60,408,000	48,525	243,907
New York Central	53.60	261.80	.....	73	.....	..... .	8,669	256	57	1,216,756,000	3,991,000	1,306,417	893,511
New-York, New Haven & Hartford	*87.86	530.58	‡130,059,200	52	38	16	11,652	79	63	‡1,254,678,065	1,123,694,301	‡3,531,068	894,734
New York, West. & Boston	23.22	73.41	11,422,794	.....	.....	1	80	45	60	97,917,969	.....	.....	11,274
Norfolk & Western	35.38	108.26	50,503,450	0	12	0	3,600	0	.....	.....	.....	21,138	330,536
Pennsylvania R. R.:													
New York Terminal	13.41	100.18	59,749,184	33	.....	1	5,281	8	55	$595,438,539	.....	1,462,994	592,496
West Jersey & Seashore	75.00	150.38	18,339,689	.... .	.....	.....	.....	107	46	261,496,377	.....	.....	.....
Paoli & Chestnut Hill	30 00	117.40	23,653,205	.....	1	.....	258	115	59	171,835,943	.....	.....	.....
Southern Pacific R. R.													
O. A. & B. Line	118.00	101.20	....	.....	... ..	.....	.....	121	55	225,635,500	.....	.....	.....
Portland Line...	146 32	141 70	.....	.....	.....	.....	.....	49	51	100,148,000	.....	.....	.....

* Not including trackage rights into New York.
† Total passenger and freight.
‡ Includes D. C. zone.
§ Includes weight of locomotive.
¶ Partial electric operation on part of zone.

DATA ON ELECTRIFICATION IN THE AMERICA'S AND IN FOREIGN COUNTRIES

In the America's

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TABLE B
General

Railroad	Section electrified	Character of service	Specific cause of electrification	Began electrical operation	Miles: Route	Miles: Main line	Miles: Yards and sidings	Miles: Total single track	System of electrification
*Baltimore & O..	Baltimore Tunnel.	Heavy passenger and freight.	Tunnel and terminal.	1895	3.6	.....	.....	7.96	600 volts, d.c.
*Boston & Maine.	Hoosac Tunnel, N. Adams, Mass	Heavy passenger and freight.	Tunnel	May, 1911	7.92	15.84	5.47	21.31	11,000 volts, 1 ϕ, 25 ~
*Butte, Anaconda & Pacific.	Butte, Anaconda, Mont.	Heavy passenger and freight.	General economy.	May, 1913	25.30	25.30	97.00	122.30	2,400 volts, d.c.
*Chic., Milwaukee & St. Paul.	Harlowton, Avery, Mont.	Heavy passenger and freight.	General economy.	December, 1915	437.6	437.6	141.9	579.5	3,000 volts, d.c.
*Chic., Milwaukee & St. Paul.	Othello — Seattle, Tacoma, Wash.	Heavy passenger and freight.	General economy.	August, 1919	209.1	212.1	68.8	280.9	3,000 volts, d.c.
*Erie	Rochester — Mt. Morris, N. Y.	M.v. passenger and freight.	.....	June, 1907	34.	34.	4.	38.	11,000 volts, 1 ϕ, 25 ~
*Grand Trunk....	Port Huron, Mich. —Sarnia, Ontario.	Heavy passenger and freight.	Tunnel	May, 1908	3.8	6.5	5.5	12.	3,300 volts, 1 ϕ, 25 ~
*Great Northern..	Cascade Tunnel, Wash.	Helper.	Tunnel	July, 1909	3.5	.....	2.5	.....	6,600 v., 3 ϕ. 25 ~ dbl. trolley.

(Continued on page 311)

TABLE B (Continued)

*Long Island ...	Sub'rb'n lines from Brooklyn and New York, N. Y.	Suburban pass'ng'r.	Tunnel and terminal	June, 1905	86.5	197.6	29.6	227.2	600 volts, d.c.
Michigan Central.	Detroit River Tun., Detroit, Mich.—Windsor, Canada.	Heavy passenger and freight.	Tunnel and terminal.	1910	6.25	.....	.....	24.	600 volts, d.c.
New York Cent'l.	New York—Harmon, N. Y.	Heavy and suburban passenger.	Tunnel and terminal.	1906	34.	.....	.....	268.	600 volts, d.c.
N. Y. Connecting.	Over East River, New York, N. Y.	Heavy passenger and freight.	Connecting P. R. R. and N. Y., N. H. & H.	1918	5.5	.....	.....	11.	11,000 volts, a.c., 1 ϕ, 25 ~.
*New York, New Haven & Hartf'd.	New York, N. Y. —New Haven, Conn	Heavy passenger and freight.	Terminal and general economy.	July, 1907	83.2	333.0	186.0	519.0	11,000 volts, 1 ϕ, 25 ~.
*New York, Westchester & Boston.	Harlem River, White Plains, Larchmont, N. Y.	Suburban pass'ng'r.	.....	1912	22.72	59.74	4.30	64.04	11,000 volts a.c., 1 ϕ, 25 ~.
*Norf'k & West'n.	Bluefield — Vivian, W. Va.	Heavy freight....	Grade and general economy.	1914	30.	.....	.....	108.26	11,000 volts, 1 ϕ, 25 ~.
*Oregon Electric..	Portland—Eugene, Oregon.	Passenger and freight.	.....	1912	122.	.....	.....	.....	1,200 volts, d.c.
	Portland — Forest Grove, Oregon.				27	.....	.....	.....	
*Pennsyl. System.	Sunnyside Yard, L'g Island—Manhattan Trans. N. J.	Heavy passenger.	Tunnel and terminal.	1910	13.5	.....	.....	110.0	675 volts, d.c.
*Pennsyl. System.	Philadelphia, Paoli, Chestnut Hill, Pa.	Suburban pass'ng'r.	Term. congestion and economy.	Paoli, Sept., 1915 / Chestnut Hill, Apr., 1918	30.0	....	.....	117.28	11,000 volts, 1 ϕ, 25 ~.
Pennsyl. System..	Camden, Millville, Atlantic City, N. J.	Passenger—express and local	Economy.	1906	75.	....	.....	150.38	600 volts, d.c.
*South'n Pac.—T.	Portland, Corvallis.	Interurban pass...	.....	January, 1914	146.	147.	.....	162.	1,500 volts, d.c.
Portland Div's'n.	Berkley—Alameda,	Suburban	.....	June, 1911	52.25	100.81	14.	114.81	1,200 volts, d.c.
Oakl'd, Alameda & Berkley.	Oakland, Cal.								
Spokane & Inland.	Spokane, Moscow & Cœur d'Alene.	Passenger and freight.	.....	.....	127	129.5	1.5	131.	6,600 volts, a.c., 1 ϕ, 25 ~.
*Visalia Electric..	Visalia — Lemon Cove, Elderwood, Cal.	Passenger and freight.	Economy.	March, 1908	.....	31.4	7.9	39.3	3,300 volts, 1 ϕ, 15 ~.
*Canadian Nat'l..	Montreal, Canada:	Heavy passenger.	Tunnel and terminal.	October, 1918	8.	13.	8.	17.	2,480 volts, d.c.
Paulista	Campinas, Jundiahy, Brazil.	Passenger and freight.	Economy — coal mostly imported.	1921	23.5	.....	.....	.....	3,000 volts, d.c.

TABLE C
Power Distribution

		Third rail construction							Overhead construction							
		Miles		Size, rail	On — side	Gage line running rail to gage line 3rd rail: Horizontal	Gage line running rail to gage line 3rd rail: Vertical	Bonds, c.m.	Miles		Messenger: Type	Messenger: Material	Messenger: Size	Auxiliary messenger: Material	Auxiliary messenger: Size
	Railroad	Route	Track						Route	Total					
1	*Baltimore & Ohio	3.6	7.96	70 & 100	Top	2′ 5 3/16″	3½″	400,000	....	....	.....	.....	....	.....	....
2	*Boston & Maine	....	....	....	....	....	....	....	7.92	21.31	[1]Single catenary [2]Single catenary	Steel Copper	5/16″ 5/8″	Copper Copper	4/0 1/0
3	*Butte, Anaconda & Pacific	....	....	....	....	....	....	....	25.30	122.5	Catenary	Steel	½″	.....	....
4	*[3]Chic., Milwau. & St. Paul	....	....	....	....	....	....	....	437.6	579.5	Single catenary—double trolley	Steel	½″	.....	....
5	*[4]Chic., Milwau. & St. Paul	....	....	....	....	....	....	....	209.1	280.9	Single catenary—double trolley	Steel	½″	.....	....
6	*Erie	....	....	....	....	....	....	....	34.	38.	Single catenary	Steel	7/16″	Copper	3/0
7	*Grand Trunk	....	....	....	....	....	....	....	3.8	12.	Single catenary	Steel	1/16″ to 5/8″	.....	....
8	*Great Northern	....	....	....	....	....	....	....	....	....	Cross catenary—double trolley	.....	....	.....	....
9	*Long Island	86.50	227.2	100 & 150	Top	2′ 2″	3½″	Various	4.1	....	.....	.....	....	.....	....
10	Michigan Central	....	....	....	....	....	....	....	....	....	.....	.....	....	.....	....
11	N. Y. Cent. & Hudson River	....	....	70	Under	2′ 2 13/16″	2¾″	...	....	....	.....	.....	....	.....	....
12	*New York Connecting	....	....	....	....	....	....	....	4.7	11.6	Catenary	Steel	5/16″	Copper	2/0
13	*N. Y., N. H. & Hartford	....	....	....	....	....	....	....	[5]22.9	91.	Double catenary	Steel	5/16″	.....	....
14	*N. Y., N. H. & Hartford	....	....	....	....	....	....	....	[6]1.1	4.5	Compound cat'n'y	Steel	1¼ only 2	Steel	5/8″

(Continued on page 313)

TABLE C (Continued)

15	*N. Y., N. H. & Hartford.	....	....	....	....	....	....	....	[7]34.9	141.5	Compound cat'n'y	Steel	7/8"	Steel	5/8"
16	*N. Y., N. H. & Hartford.	....	....	....	....	....	....	....	[8]10.8	22.6	Single catenary	Steel	5/8"	.....	....
17	*N. Y., N. H. & Hartford.	....	....	....	....	....	....	....	[9]1.69	7.1	Single catenary	Steel	5/8"	.....	....
18	*N. Y., N. H. & Hartford.	....	....	....	....	....	....	....	[10]9.58	57.5	Compound cat'n'y	Steel	7/8"	Steel	5/8"
19	*N. Y., N. H. & Hartford.	....	....	....	....	....	....	....	[11]7.9	7.9	Single catenary	Steel	7/8"	.....	....
20	*N. Y., Westchester & Bos.	....	....	....	....	....	....	....	[12]7.9	31.6	Compound cat'n'y	Steel	7/8"	Steel	5/8"
21	*N. Y., Westchester & Bos.	....	....	....	....	....	....	....	[13]8.5	17.	Compound cat'n'y	Steel	5/8"	Copper	4/0
22	*N. Y., Westchester & Bos.	....	....	....	....	....	....	....	2.	4.	Compound cat'n'y	Steel	7/8"	Steel	5/8"
23	*Norfolk & Western	....	....	....	....	....	....	....	23.	46.	Single catenary	Steel	1/2"	Steel and Copper	1/0
24	*Oregon Electric	....	....	....	....	....	....	....	122.	180.	Single catenary	Steel	7/16"	.....	....
25	*[14]Pennsylvania System	....	110	25 & 150	Top	....	....	....	....	....	.....	.....	....	.....	....
26	[15]Pennsylvania System	....	....	....	....	....	....	....	30.	117.28	Single catenary	Steel	1/2"	Copper	1/0 rd.
27	[16]Pennsylvania System	....	141.7	100	Top	2' 2"	3.5"	2-500,000	....	....	.....	.....	....	.....	....
28	*South'n Pac., Portland Div.	....	....	....	....	....	....	....	146.	162.	Single catenary	Steel	7/16"	.....	....
29	*Southern Pacific (Oakland, Alameda & B.).	....	....	....	....	....	....	....	52.25	114.81	Single catenary	Steel	7/16"	.....	....
30	*Visalia Electric	....	....	....	....	....	....	....	22.	45.	Single catenary	Steel	7/16"	.....	....
31	*Canadian National	....	....	....	....	....	....	....	9.	10.	Catenary	Steel / Phosphor-bronze	1/4" / 7/8"	.....	....

*Data given in 1920 report corrected and extended by railroad. [1]Outside of tunnel. [2]Inside tunnel. [3]Harlowton—Avery. [4]Othello—Seattle—Tacoma. [5]Woodlawn—New Rochelle—Stamford. [6]Stamford—Glenbrook. [7]Glenbrook—New Haven.

[8]Glenbrook—New Haven. [9]Harlem River Branch. [10]Harlem River Branch. [11]New Canaan Branch. [12]Maine line. [13]White Plains Branch. [14]Manhattan Transfer through New York station to Sunny Side yard. [15]Broad Street Station, Philadelphia—Paoli and Chestnut Hill. [16]Camden—Atlantic City and Millville.

(Continued on page 314)

TABLE C (Continued)
Power Distribution

	Overhead construction											
	Contact wire									Feeders		
	Material	Size	Height above rail — Normal	Max.	Min.	Type of support	Av. distance between anchor bridges — Spacing	anchor bridges	Return current through	Positive	Negative	Track bonds
1	.....	....	.....	.....	.....	.....	....	.....	Rails	.....	.....	400,000 c.m.
2	Phono-electric	4/0	22' 0"	23' 0"	19' 5"	Steel bridges	150'	.....	Rails	.....	.....	2-4/0
	Phono-electric	2-4/0	15' 10'	16' 7"	15' 10"	Brackets	100'	.....	Rails	.....	.....	.....
3	Copper	4/0	22' 4"	25' 0"	17' 4"	Wood	150'	.....	Rails	600,000 c.m. main line	1-4/0	4/0
4	Copper	Main 2-4/0 / Siding 1-4/0	24' 2"	26' 0"	17' 0"	Wood	150'	1 mile	Rails	Size varies	1-4/0 supplementary	Single & double, pin, 250,000 c.m.
5	Copper	Main 2-4/0 / Siding 1-4/0	24' 2"	26' 0"	17' 0"	Wood	150'	1 mile	Rails	Size varies	1-4/0 supplementary	Single & double, pin, 250,000 c.m.
6	Steel	3/0	21' 0"	.....	18' 0"	Steel & wood	120'	.....	Rails	.....	.....	.....
7	Copper	4/0 & 300,000 c.m.	22' 0"	.....	.....	Steel bridges / Brackets	250' / 12'	.....	Rails	.....	.....	4/0 and 2-300,000 c.m.
8	.....	....	24' high, 5' apart	.....	.....	Wood	100'	1,000	Rails	.....	.....	1-4/0
9	.....	....	.....	.....	.....	.....	....	.....	Rails	.....	.....	.....
10	.....	....	.....	.....	.....	.....	....	.....	Rails	.....	.....	.....
11	.....	....	.....	.....	.....	.....	....	.....	Rails	.....	.....	.....
12	Phono-electric	3/0	22' 0"	22' 0"	17' 6"	Steel	....	.....	Rail	.....	.....	1/0 Duplex
13	Steel & phono-electric	4/0	22' 0"	22' 0"	15' 4½"	Steel bridges	300'	2.6 miles	3rd wire & rail	New Rochelle—Woodlawn, 2-4/0, 2-2/0 / New Rachelle—Stamford, 4-4/0	.....	4/0 Flexible

(Continued on page 315)

TABLE C (Continued)

14	Steel & phono-electric	4/0	20' 10"	22' 0"	18' 0"	Steel [ ]	300'	.....	3rd wire & rail	4-4/0	.....	1/0 Duplex
15	Steel & phono-electric	4/0	20' 10"	22' 0"	15' 8"	Steel bridges	300'	4.2 miles	3rd wire & rail	4-4/0	.....	1/0 Duplex
16	Steel & phono-electric	4/0	20' 10"	22' 0"	15' 10½"	Steel bridges	300'	2.6 miles	3rd wire & rail	4-4/0	.....	1/0 Duplex
17	Steel & phono-electric	4/0	20' 10"	22' 0"	18' 5"	Steel	300'	1.1 miles	3rd wire & rail	4-4/0	.....	1/0 Duplex
18	Steel & phono-electric	4/0	20' 10"	22' 0"	16' 0"	Steel bridges	300'	2.4 miles	3rd wire & rail	4-4/0	.....	1/0 Duplex
19	Steel	4/0	22' 0"	22' 0"	22' 0"	Wood & steel	150'	.....	Rail	.....	.....	4/0 Flexible
20	Steel	4/0	.....	.....	.....	Steel bridge	300'	.....	3rd wire	4-4/0	.....	Pin terminal
21	Phono-electric	4/0	22' 0"	.....	.....	Steel bridge	300'	.....	3rd wire	2-4/0	.....	Pin terminal
22	Steel	4/0	.....	.....	.....	Steel bridge	300'	.....	3rd wire	{ 3-4/0 22,000 v. } { 1-4/0 11,000 v. }	.....	Pin terminal
23	Phono-electric	3/0 grooved	23' 9"	.....	16' 0"	Steel bridges	300'	.....	Rails	.....	.....	Equivalent .275" rd.
24	Copper	3/0 grooved	21' 0"	23' 0"	17' 0"	Wood	150'	1 mile	Rails	300.000 c.m.	.....	4/0 welded
25	.....	....	.....	.....	.....	.....	....	.....	Rails	.....	.....	.....
26	Phono-electric	3/0	22' 0"	.....	.....	Tubular steel	300'	½ mile	Rails	.....	.....	.....
27	.....	....	.....	.....	.....	.....	....	.....	Rails	.....	.....	2-400,000 c.m.
28	Copper	4/0	22' 0"	.....	.....	Cedar	150'	.....	Rails	Alum. { 336,420 c.m. } { 636,000 c.m. }	.....	4/0
29	Copper	4/0	22' 0"	.....	.....	{ Steel bridges } { and poles }	{ 240' } { 120' }	.....	Rails	Alum. { 1,590,000 c.m. } { 1,192,000 c.m. } { 800,000 c.m. }	.....	4/0 double
30	Copper	3/0	22' 0"	.....	.....	{ Red wood } { Cedar }	{ 120' } { 150' }	.....	Rails	.....	.....	2-1/0
31	{ Copper } { Phono-electric }	{ 4/0 } { 4/0 }	22' 6"	22' 6"	16' 0"	Cedar	150'	.....	Rails	4/0	.....	4/0 welded

TABLE D

Power Generation

Railroad	Power Supply: Chief Source	Power Supply: Generated or Purchased	Prime Movers: No.	Prime Movers: Mfg.	Prime Movers: Rating	Volt-age	Cur-rent	Phases	Cycles	Per cent power Regenerated
*Baltimore & Ohio	Con. Gas, Elec. Light & Power Co.	Purchased								0.00
*Boston & Maine	New England Power Co	Purchased				11,000	a.c.,	3	25	0.00
*Butte, Anaconda & Pacific	Great Falls Power Co., hydro-electric.	Purchased								0.00
*Chicago, Milwaukee & St. Paul.	Montana Power Co. & Thompson Falls Power Co.	Purchased				6,600	v.			10-11
*Chicago, Milwaukee & St. Paul.	Wash. Water Power Co.—Puget Sound T., L. & P.	Purchased								10-11
*Erie	Niagara, Lockport & Ont. P. Co..	Purchased								0.00
*Grand Trunk	Detroit Edison Co	Purchased								
	Grand Tr. Ry. Co. Power Plant..	Generated	2	W. E. & Mfg. Co.,	1,250 kw. turbos,	3,300	v., a.c.,	3	25	0.00
*Great Northern	Hydro-Electric	Generated	2		2,500 k. v. a. hydraulic turb. gen.	6,600	v., a.c.,	3	35	....
*Long Island	Penna. R. R. Long Island P. P...	Purchased	See Pennsylvania System			11,000	v., a.c.,	3	25	0.00
Michigan Central	Detroit Edison	Purchased								0.00
New York Central & Hud. River.	N. Y. C. Power Plants, Port Morris & Glenwood.	Generated	G. E. turbines, total cap. 60,000 kw...							0.00
New York Connecting	N. Y., N. H. & H. R. R. Cos Cob Power Plant.	Purchased				11,000	v., a.c.,	3	25	0.00
*N. Y., N. H. & Hartford	N. Y., N. H. & H. R. R. Cos Cob Power Plant.	Generated	3	W. E. & Mfg. Co. turbo-gen.,	3,750 k. v. a.	11,000	v., a.c.,	3	25	0.00
			4	W. E. & Mfg. Co. turbo-gen.,	5,000 k. v. a.					
			1	W. E. & Mfg. Co. turbo-gen.,	4,200 k. v. a.					
*N. Y., Westchester & Boston	N. Y., N. H. & H. R. R. Cos Cob Power Plant.	Purchased	See N. Y., N. H. & H.			11,000	v., a.c.,	3	25	0.00
*Norfolk & Western	N. & W. R. R. Blue Stone Power Plant.	Generated	4	W. E. & Mfg. turbo-gen.,	10,000 kw.	11,000	v., a.c.,	3	25	....
*Oregon Electric	Portland Ry. Lt. & P. Co	Purchased				11,000	v., a.c.,	3	33	0.00
*Pennsylvania System—N. Y.	Penn. R. R. Long Is. Power Plant	Generated	2	W. E. & Mfg. Co. turbo-gen.,	5,500 kw.	11,000	v., a.c.,	3	25	0.00
			2	W. E. & Mfg. Co. turbo-gen.,	8,000 kw.					
			2	W. E. & Mfg. Co. turbo-gen.,	20,000 kw.					
*Pennsylvania System—Paoli	Philadelphia Electric Co	Purchased				13,200	v., a.c.,	3	25	0.00
Penna System—Atlantic City	Penn. R. R. Co., Westville P. P.	Generated	4	G. E. 2,000 kw. surbo-gen.		6,600	v., a.c.,	3	25	0.00
*Southern Pacific										
Portland Division	Portland Ry., Lt., and Power Co.	Purchased								
Oakland, Alameda & Berkeley	Fruitvale Pwr. Plant of O. A. & B.	Generated	2	W. E. & Mfg. Co. turbo-gen.,	7,500 kw.	13,200	v., a.c.,	3	25	0.00
Spokane & Inland										
*Visalia Electric	Southern California Edison Co...	Purchased								0.00
*Canadian National	Part of Hydro-Electric net work..	Purchased								0.00
Paulista	Sao Paulo Light & Power Co....	Purchased	Hydro-electric			88,000	v., a.c.,	3	60	....

*Data given in 1920 report corrected and extended by Railroad.

TABLE E

Sub-Stations

Railroad	Number	Type	Spacing miles	Transformers: Number	Transformers: Type	Transformers: Rating	Transformers: Ratio	Rotary Converters: Number	Rotary Converters: Type	Rotary Converters: Rating	Motor Generators: Number	Motor Generators: Type	Motor Generators: Rating	Transformed to: Voltage	Transformed to: Current	Transformed to: Phase	Transformed to: Cycle
[1]Baltimore & Ohio	3	Rotary converter.	....	..	.....	.....	.....	4	G E.	{3-1,000 kw. 1-2,000 kw.}	.....	.....	.....	600	d.c.	..	..
[2]Boston & Maine	3	Switching	....	..	.....	.....	.....	..	.....	.....	.....	.....	.....	.....	...	..	..
[3]Butte, Anaconda & Pacific	2	Motor generator.	26	..	O. I. W. C., 1 ϕ	2,400 k.v.a.	100,000-2,400	..	.....	.....	7 G. E.	1,200-24,005 3 unit syn. motor	1,000 kw.	2,400	d.c.	..	..
[4][1]Chic., Milwau. & St. Paul	14	Attended motor generator.	32.7 av.	{9 $\Delta\Delta$ 23 $\Delta\Delta$	G. E. Co., O. I. S. C., 3 ϕ 60 ~. G. E. Co., O. I. S. C., 3 ϕ 60 ~.	1,900 k.v.a. 2,500 k.v.a	102,000 {2,300 1,150} 102,000 {2,300 1,150}	..	.....	.....	9 G. E. 23 G. E.	3 unit syn. motor 3 unit syn. motor	1,500 kw. 2,000 kw.	3,000	d.c.	..	..
[4][2]Chic., Milwau. & St. Paul	5 & 3	Attended motor generator.	28 av.	{9 Y Δ 6 Y Δ	G. E. Co., O. I. S. C., 3 ϕ 60 ~. West., O. I. S. C., 3 ϕ 60 ~.	2,500 k.v.a.	102,000 {2,300 1,150}	..	.....	.....	{8 G. E. 6 West.	3 unit syn. motor 3 unit syn. motor	2,000 kw. 2,000 kw.	3,000	d.c.	..	..
[4]Erie	1	Transformer ...	.....	3	O. I. W. L., 1 ϕ	750 k.v.a.	60,000-11,000	..	.....	.....	.....	.....	.....	11,000	a.c.	1	25
[4]Grand Trunk	..	.....	....	..	.....	.....	.....	..	.....	.....	.....	.....	.....	.....	...	..	..
[4]Great Northern	1	Transformer ...	....	4	.....	833 kw.	33,000-6,600	..	.....	.....	.....	.....	.....	6,600	a.c.	3 ϕ	25
[4]Long Island	[5]14	Rotary converter.	3 to 8	..	.....	.....	.....	45	West.	1,000-1,500 kw.	.....	.....	.....	650	d.c.	.	..
[4]Long Island	[5]3	Rotary converter.	.....	..	.....	.....	.....	..	.....	2,000-3,000 kw.	...	.....	.....	650	d.c.	..	..
Michigan Central	1	Rotary converter.	....	..	.....	.....	.....	2	G. E.	.....	...	.....	1,000 kw	600	d.c.	..	..
N. Y. Cent. & H'ds'n River	..	Rotary converter.	....	..	.....	.....	.....	..	{G. E. West.	20,000 kw. 245,000 kw.	.....	.....	.....	600	d.c.	..	..
New York Connecting	..	.....	....	..	.....	.....	.....	..	.....	.....	.....	.....	.....	.....	...	..	..
[4]N. Y., N. H. & Hartford	22	Transformer, remote.	3.87	1	Auto. O. I. S. C., 1 ϕ	2,000 k.v.a	22,000-11,000	..	.....	.....	.....	.....	.....	11,000	a.c.	1	25
[4]N. Y., Westchester & Bos.	3	Transformer ...	9.	3	Auto. O. I. S. C., 1 ϕ	2,000 k.v.a	22,000-11,000	..	.....	.....	.....	.....	.....	11,000	a.c.	1	25
[4]Norfolk & Western	5	Transformer ...	....	12	O. I. W. C., 1 ϕ	{4 2,000 k.v.a. 6-3,000 k.v.a. 2-5,000 k.v.a.}	44,000-11,000	..	.....	.....	...	.....	.....	11,000	a.c.	1	25
[4]Oregon Electric	[6]9	Rotary converter.	20	36	8-1 ϕ, 1-3 ϕ	185 k.v.a.	60,000-11,000	13	G. E.	500 kw.	...	.....	.....	1,200	d.c.	..	..
[4][6]Pennsylvania System	4	Rotary converter.	....	36	A. B.	750 k.v.a.	.....	12	West.	2,000 kw.	.....	.....	.....	600	d.c.	..	..
[4][6]Pennsylvania System	6	Transformer, remote.	....	12	1 ϕ	6-2,000 k.v.a. 6-3,000 k.v.a.	44,000-11,000 44,000-11,000	..	.....	.....	.....	.....	.....	11,000 11,000	a.c. a.c.	1 1	25 25
[7]Pennsylvania System	8	Rotary converter.	3.6 to 12.5	[6]66	A. B.	{12-185 kw. 36-275 kw. 18-370 kw.}	.....	22	G. E.	{4- 500 kw. 12- 750 kw. 6-1,000 kw.}	...	.....	.....	675	d.c.		
[4]South'n Pac.—Portl'd Div.	..	Motor generator and converter.	25	..	.....	.....	.....	2	West. 2 unit	1,000 kw.	7	2 unit syn. motor	500 kw	1,500	d.c.		
[4]Southern Pacific (Oakland, Alameda & Berkly).	3	Rotary converter.	10	..	.....	.....	.....	10	G. E. 2 unit	1,500 kw.	..	.....	.....	1,200	d.c.		
Spokane & Inland	..	.....	....	..	.....	.....	.....	..	.....	.....	.....	.....	.....	.....	...	..	..
[4]Visalia Electric	5	Transformer ...	....	5	O. I. S. C.	300 k.v.a.	11,000-3,300	..	.....	.....	.....	.....	.....	3,300	a.c.	1	15
[4]Canadian National	..	.....	....	..	.....	.....	.....	..	.....	.....	2 G.E.	1,200-2,400	1,500 kw.	2,400	d.c.	.	..
Paulista	1	Motor generator.	....	3	3 ϕ 60 ~.	1,900 k.v.a.	88,000-2,300	..	.....	.....	3	3 unit syn. motor	1,500 kw.	3,000	d.c.		

[1]Data given in 1920 report corrected and extended by railroad.
[2]Harlowton—Avery.
[3]Othello—Seattle—Tacoma.
[4]Housed.
[5]Portable.
[6]Manhattan Transfer through New York Station to Sunny Side yard.
[7]Broad Street Station, Phdadelphia—Paoli and Chestnut Hill.
[8]Camden—Atlantic City and Millville.
[9]Storage battery reserve.
[10]Eight housed, 1 portable.

See also Table H on page 322.

TABLE F

ELECTRIC LOCOMOTIVES USED IN THE AMERICAS

COMPANY NO	RAILROAD	KEY NO	SERIES NO	NO IN SERVICE	YEAR PLACED IN SERVICE	MFG CO.	CLASS OF SERVICE	CONTACT VOLTAGE	CONDUCTOR TYPE	TYPE OF LOCO	CLASSIFICATION BY WHEELS	DRIVING WHEELS NO	DRIVING WHEELS DIAM	TRUCK WHEELS NO	TRUCK WHEELS DIAM.	ARTICULATED TRUCKS	WHEEL BASE RIGID	WHEEL BASE TOTAL
1	Baltimore & Ohio R R Co	1a	6-9	4	1903-04	GE Co	Frt	600	3rd Rail	O C	0-4-4-0	8	42 in	0	—	No	14 6	14 6
		1b	11-12	2	1910	"	Pass-Et	600	" "	"	0-4-4-0	8	50 in	0	—	Yes	9-6	27-6
		1c	13-14	2	1912	"	" "	600	" "	"	0-4-4-0	8	50 in	0	—	Yes	9-6	27-6
2	Bethlehem-Chile Iron Mines Co	2	6-7-8	3	1920	"	Frt	2400	3rd Rail & Catenary	"	0-4-4-0	8	52 in	0	—	Yes	11-0	35-8
3	Boston & Maine	3a	5000-4	5	1911	Baldwin-Westinghouse	Pass-Et	11000	Catenary	A C-10	2-8-4-2	8	63 in	4	42 in	Yes	7-0	38-6
		3b	5005-6	2	1917	" "	" "	11000	"	"	2-8-4-2	8	63 in	4	42 in	Yes	7-0	38-6
4	Butte Anaconda & Pacific	4a	39-64	26	1913-17	GE Co	Frt	2400	Catenary	D C	0-8-4-0	8	46 in	0	—	Yes	8-8	26-0
		4b	65-66	2	1913	"	Pass	2400	"	"	0-8-4-0	8	46 in	0	—	Yes	8-8	26-0
5	Canadian Nat'l Rys (Mt. Royal)	5	600-5	6	1918	GE Co	Pass-Et	2400	3rd Rail & Catenary	D C	0-4-4-0	8	46 in	0	—	Yes	8-8	26-0
6	Chicago, Milwaukee & St Paul	6a	10050-3	6	1917-18	GE Co	Switch	3000	3rd Rail	O C	0-8-8-0	8	40 in	0	—	No	8-0	30-4
		6b	10200-41	42	1916	"	Frt	3,000	"	"	4-4-4-4-4-4	16	52 in	8	36 in	Yes (2 Units)	10-6	102-8
		6c	10250-4	5	1920	"	Pass	3000	"	"	6-8-8-6	24	44 in	4	36 in	Yes	13-9	67-0
		6d	10300	1	1920	Baldwin-Westinghouse	Frt.	3000	"	"	4-6-2-2-6-4	12	68 in	12	36 in	Yes	16-9	79-10
		6e	10301-3	3	1920	"	Pass	3000	"	"	4-6-2-2-6-4	12	68 in	12	36 in	Yes	16-9	79-10
7	Grand Trunk (St Clair Tunnel)	7	2655-60	3	1908	Baldwin-Westinghouse	Pass-Et	3300	Catenary	A C-10	0-6-0+0-6-0	12	62 in	0	—	No (2 Units)	16-0	45-5½
8	Great Northern Ry.	8	5000-3	4	1909	GE Co	Pass Et	6600	Direct Suspension	A C-14	0-4-4-0	8	60 in	0	—	Yes	11-0	34-9
9	Long Island R.R.	9	323	1	1917	Baldwin	Frt.	650	3rd Rail	D C	0-4-4-0	8	56 in	0	—	NO	7 2	26-1
10	Michigan Central R. R	10a	7500-5	6	1903	GE Co	Pass-Et	600	3rd Rail	D C	0-4-4-0	8	48 in	0	—	Yes	9-6	27-6
		10b	7506-9	4	1914	"	"	600	"	"	0-4-4-0	8	48 in	0	—	Yes	9-6	27-6
11	New York Central	11a	1100-34	35	1906	GE Co	Pass	600	3rd Rail	D C	4-8-4	8	44 in	8	33 in	NO	13-0	32-6
		11b	1135-46	12	1906-09	"	"	600	" "	"	4-8-4	8	44 in	8	36 in	NO	13-0	36-0
		11c	1147-56	10	1913	"	"	600	" "	"	4-4-4-4	16	36 in	0	—	Yes	5-0	45-7
		11d	1157-72	16	1914-18	"	"	600	" "	"	4-4-4-4	16	36 in	0	—	Yes	5-0	46-5
12	New York, New Haven & Hartford	12a	01-041	41	1907	Baldwin-Westinghouse	Pass	6,000 (1,100)	3rd Rail & Catenary	D.C. & A.C.-10	2-4-4-2	8	62 in	4	33 in	NO	8-0	30-10
		12b	068	1	1916	GE Co	Frt. & Switch	11000	Catenary	A C-14	4-4-4-4	8	54 in	8	33 in	Yes	10-6	54-10
		12c	069	1	1910	Baldwin-Westinghouse	Pass. Et	6,000 (1,100)	3rd Rail & Catenary	D.C. & A.C.-10	2-4-4-2	8	63 in	4	36 in	NO	11-0	39-0
		12d	070	1	1910	"	Frt & Switch	11000	Catenary	A C-10	2-4-4-2	8	57 in	4	36 in	Yes	8-0	43-6
		12e	071	1	1910	"	Pass	6,000 (1,100)	3rd Rail & Catenary	D.C. & A.C.-10	2-4-4-2	8	63 in	4	42 in	Yes	7-0	38-6
		12f	072	1	1911	"	"	" "	"	"	2-4-4-2	8	63 in	4	36 in	Yes	7-0	38-6
		12g	073-075	3	1911-13	"	"	" "	"	"	2-4-4-2	8	63 in	4	36 in	Yes	8-0	40-6
		12h	076-0111	36	1913	"	Frt	11000	Catenary	A C-10	2-4-4-2	8	63 in	4	36 in	Yes	8-0	40-6
		12i	0220	1	1911	"	Switch	11000	Catenary	A C-10	0-4-4-0	8	63 in	0	—	Yes	7-0	23-6
		12j	0221-14	14	1912	"	"	"	"	"	0-4-4-0	8	63 in	0	—	Yes	7-0	23-6
		12k	0215	1	1912	"	"	"	"	"	0-4-4-0	8	63 in	0	—	Yes	7-0	23-6
		12l	0300-4	5	1913	"	Pass	6,000 (1,100)	3rd Rail & Catenary	D.C. & A.C.-10	2-6-2-2-6-2	12	63 in	8	36 in	Yes	14-3	53-6
13	New York Westchester & Boston	13	301	1	1912	Baldwin-Westinghouse	Frt.	11000	Catenary	A.C.-10	0-4-4-0	8	63 in	0	—	Yes	7-0	23-6
14	Norfolk & Western	14	2500-11	12	1915	Baldwin-Westinghouse	Frt.	11000	Catenary	A.C.-10 A.C. Unit	2-8-8-2+2-8-8-2	16	62 in	8	30 in	Yes	11-0	94-10
15	Pennsylvania System	15	3931	1	1917	Penna. R.R.	Frt	11000	Catenary	A.C.-10 A.C. Unit	2-6-6-2	12	72 in	4	36 in	Yes	13-4	63-11
		15a	32-33	2	1910	Penna. R.R.	Pass	600	3rd Rail & Catenary	D.C	4-4-4-4	8	68 in	8	36 in	Yes	7-2	55-11
		15b	112-21 & 112-21A	31	1910	"	Switch	600	"	"	4-4-4-4	8	72 in	8	36 in	Yes	7-2	55-11
		15c	3951	1	1910	"	Switch	600	"	"	0-4-4-0	8	56 in	0	—	Yes	8-6	26-1
16	Paulista Railway (Sao Paulo)	16a	208-11	4	1921	GE Co	Pass	3000	Catenary	D. C.	4-4-4-4	8	42 in	8	36 in	Yes	7-9	46-0
		16b	200-207	8	1921	"	Frt.	3000	"	"	0-4-4-0	8	42 in	0	—	Yes	8-8	26-8
		16c	212-221	2	1921	Westinghouse	Pass	3000	"	"	2-2-2-2	8	63 in	4	36 in	Yes	8-4	41-2
		16d	2194-219	2	1921	"	Frt.	3000	"	"	0-6-6-0	12	40 in	—	—	Yes	14-0	37-0
17	Chilean State Rys.	17a	—	15	1923	"	Frt.	3000	Catenary	D.C.	0-6-6-0	12	42 in	—	—	Yes	13-9	37-0
		17b	—	6	"	"	Pass	3000	"	"	2-6-6-2	12	42 in	4	30 in.	Yes	14-5	48-4
		17c	—	11	"	"	Pass	3300	"	"	0-4-4-0	8	42 in	—	—	Yes	9-0	28-0
		17d	—	7	"	"	Switch	3300	"	"	0-4-4-0	8	42 in	—	—	—	8-6	27-4

(Continued on page 319)

TABLE F (Continued)

ELECTRIC LOCOMOTIVES USED IN THE AMERICA'S

WEIGHTS – LB					DIMENSIONS			TYPE CONTROL	MOTORS				TRACTIVE EFFORT – LB					SPEED – M.P.H.			HORSE POWER OF LOCOMOTIVE			KEY NO
TOTAL	ON DRIVERS	PER DRIVING AXLE	MECH PARTS	ELECT PARTS	LENGTH OVER ALL	WIDTH OVER ALL	HEIGHT FROM RAIL TO TOP OF PANTO'S OR TROLLEY POLES		NO	TYPE	METHOD OF DRIVE	GEAR RATIO	ONE HOUR RATING FORCE LB AT M.P.H.	PER CENT COEF OF ADHESION	CONTINUOUS RATING FORCE LB AT M.P.H.	PER CENT COEF OF ADHESION	STARTING AT 25% COEF OF ADHESION	ONE HOUR RATING	CONTINUOUS RATING	MAX. SAFE	ONE HOUR RATING FORCED VENTILATION	CONTINUOUS RATING FORCED VENTILATION	
140,000	140,000	40,000	116,000	44,000	29'-7	9'-2"	13'-8	No	4	GE 658	GEAR	15/81	(1)34,000	22.5%	—	—	40,000	8.0	—	—	(2)800	—	1a
185,000	185,000	46,250	119,000	66,000	39'-6	10'-2½	14'-5	No	4	GE 709A	Twin Gear	25/16	(1)25,000	13.5%	12,800	6.9%	46,250	16.4	19.6	45	(2)1,100	670	1b
200,000	200,000	50,000	135,000	65,000	39'-6"	10'-2½	14'-5	No	4	GE 709A	Twin Gear	25/16	(1)25,000	12.5%	12,800	6.4%	50,000	16.4	19.6	45	(2)1,100	670	1c
239,000	239,000	59,750	170,600	118,400	49'-6	10'-0¾	16'-7½	Yes	4	GE 253A	Twin Gear	15/82	(1)42,000	17.6%	35,200	14.7%	59,150	12.2	12.7	35	(2)1370	1190	2
280,000	204,000	51,000	141,800	118,200	48'-5	10'-3	14'-5	No	4	GE 903	Quill	21/56	23,000	11.3%	20,500	10.0%	51,000	24.4	25.6	30	1600	1,400	3a
285,500	217,000	54,250	147,500	118,000	48'-0	10'-1	14'-0¾	No	4	403A	"	21/56	23,500	10.8%	21,000	9.7%	54,250	24.2	25.3	35	1510	1,415	3b
160,000	160,000	40,000	102,000	62,000	37'-4	10'-0	15'-6	No	4	GE 229A	Twin Gear	16/63	(1)30,600	19.3%	25,000	15.6%	40,000	15.4	16.2	35	(2)1200	1,030	4a
160,000	160,000	40,000	102,000	62,000	37'-4	10'-0	15'-6	No	4	GE 229A	Twin Gear	25/80	(1)20,200	12.6%	16,200	10.1%	40,000	23.4	24.6	50	(2)1200	1,030	4b
160,000	160,000	40,000	102,540	63,460	37'-4	10'-0	15'-6	No	4	GE 229A	Twin Gear	25/80	(1)20,200	12.2%	16,200	10.1%	61,500	23.4	24.6	50	(2)1200	1,030	5
143,200	143,200	35,800	90,900	62,300	41'-5	10'-1	16'-0	No	4	GE 255A	Gear	15/82	(1)21,400	15.0%	14,000	9.8%	35,800	11.5	12.8	35	(2)660	480	6a
576,000	480,000	56,250	328,000	248,000	112'-0"	10'-0	16'-8	Yes	8	GE 253	Gear	15/82	(1)45,000	18.8%	30,700	12.7%	112,500	15.25	15.9	35	(2)3440	3000	6b
521,200	457,800	38,150	284,550	236,650	96'-0	10'-0	16'-8	Yes	12	GE 100	Direct	—	(1)48,500	10.19%	42,000	9.82%	114,450	22.1	28.4	90	(2)3500	3200	6c
556,780	343,330	57,260	297,000	259,780	88'-7	11'-0¾	17'-0	Yes	6	GE 734B	Quill	15/82	(1)72,000 (2)57,000 (3)40,000	22.6 19.6 13.9%	58,000 48,000 40,000	18.2% 16.3 14.5%	84,000 84,000 84,000	(1)8.4 (2)13.0 (3)20.0	(1)8.4 (2)11.8 (3)18.4	55 55 65	(1)4200 (2)4200 4200	3400 3400 3400	6d 6e
556,780	343,330	57,260	297,000	259,780	88'-7	11'-0¾	17'-0	Yes	6	348	"	15/82	(1)72,000 (2)57,000 (3)40,000	22.6 19.6 13.9%	58,000 48,000 40,000	18.2% 16.3 14.5%	84,000 84,000 84,000	(1)8.4 (2)13.0 (3)20.0	(1)8.4 (2)11.8 (3)18.4	55 55 65	(1)4200 (2)4200 4200	3400 3400 3400	6e
264,000	264,000	44,000	147,300	116,700	58'-11	9'-8	15'-3	No	6	437	Geared	15/85	52,000	19.7%	37,000	14.0%	66,000	10.8	13.5	30	1500	1335	7
230,000	230,000	57,500	121,000	109,000	44'-2"	10'-0	15'-1	Yes	4	GE 1506	Twin Gear	19/81	38,090	16.5%	34,800	15.1%	57,500	15.1	15.2	30	1500	1,400	8
175,800	175,800	43,950	114,640	61,160	38'-8	10'-1½	13'-6	No	4	38	Geared	13/64	23,200	13.2%	15,440	8.78%	44,000	21.2	24.7	36	1200	1030.	9
200,000	200,000	40,000	135,000	65,000	39'-6	10'-2½	14'-8	No	4	GE 209A	Gear	15/81	35,000	17.5%	18,000	9.0%	40,000	11.8	14.0	40	1100	670	10a
240,000	240,000	60,000	175,000	65,000	39'-6	10'-2½	14'-8	No	4	GE 209A	"	15/81	34,000	14.2%	18,000	7.5%	60,000	12.3	14.0	40	1100	670	10b
227,700	140,900	35,225	167,700	60,000	38'-3	10'-1	14'-3½	No	4	GE 84	Direct	—	(1)21,000	14.9%	15,000	3.55%	35,225	38.5	60.0	80	(2)2200	800	11a
244,500	148,500	37,125	184,500	60,000	43'-0½	10'-1	14'-6	No	4	GE 84	"	—	(1)21,000	14.1%	15,000	3.37%	35,815	38.5	60.0	80	(2)2200	800	11b
237,000	237,000	79,625	163,000	74,000	55'-2	10'-1½	14'-6	No	8	GE 92	"	—	17,200	7.25%	11,400	4.8%	59,250	50.5	57.5	85	2320	1760	11c
265,000	263,000	33,125	177,000	88,000	56'-10	10'-1½	14'-6	No	8	GE 91	"	—	20,000	7.6%	14,000	5.28%	66,250	43.0	58.3	85	2600	2000	11d
220,140	169,050	42,263	108,140	112,000	37'-6½	10'-2	14'-3	No	4	430	Gear(1) Quill(2)	15/82	(1)9700 (2)9700	5.7% 5.7%	8400 8400	3.8% 3.8%	42263	54.5	66.0	88	1420	1125	12a
291,000	194,000	48,500	172,000	119,000	62'-0	10'-0	14'-5	No	4	GE A614	Twin Gear	33/64	27,000	13.8%	22,200	11.3%	48,500	23.0	26.4	45	1800	1600	12b
234,640	156,240	43,560	116,140	120,500	46'-0	10'-3	14'-5	No	4	GE 409A	Geared Quill	25/56	18,300	10.5%	12,600	7.2%	43,560	36.0	41.5	54	1700	1350	12c
210,000	192,000	48,000	138,000	132,000	53'-8	10'-3	14'-6	No	2	406	Twin Gear	—	16,800	8.7%	12,000	6.2%	48,000	32.0	35.6	61	1260	1044	12d
289,300	186,450	46,613	160,300	123,000	48'-0	10'-3	14'-5	No	4	403	Gear	25/56	13,200	7.1%	11,800	6.3%	46,613	37.0	48.0	55	1640	1160	12e
256,600	190,360	47,595	128,620	128,000	48'-0	10'-3	14'-3	No	4	403B	"	25/56	13,200	6.9%	11,800	6.2%	47,595	37.0	48.0	55	1600	1160	12f
245,140	189,760	47,440	133,040	115,100	50'-0	10'-3	14'-6	No	4	409C	"	25/56	18200	9.6%	12,400	6.5%	47,440	36.0	41.5	54	1700	1350	12g
219,600	165,000	41,250	120,900	98,600	50'-0	10'-3	14'-6	No	4	409C	"	25/56	18200	11.0%	12,400	7.5%	41,250	36.0	41.5	54	1700	1350	12h
158,000	158,000	39,500	79,700	78,300	37'-0	10'-1½	14'-2	No	4	410	"	15/61	23,200	14.7%	14,800	9.4%	39,500	12.2	14.5	25	750	572	12i
159,200	159,200	39,800	83,400	75,800	37'-6	10'-1½	14'-2	No	4	410	"	15/61	23,200	14.6%	14,800	9.3%	39,800	12.2	14.5	25	750	572	12j
159,200	159,200	39,800	83,400	75,800	37'-6	10'-1½	14'-2	No	4	410	"	15/61	23,200	14.6%	14,800	9.3%	39,800	12.2	14.5	25	750	572	12k
350,000	233,000	38,833	179,500	176,500	69'-0	10'-2	14'-2	No	6	443C1	"	15/61	21,000	9.0%	14,500	6.2%	58,250	45.6	52.5	70	2550	2025	12l
159,200	159,200	39,800	83,400	75,800	37'-6	10'-0	14'-2	No	4	410	Geared Quill	15/61	23,200	14.5%	14,800	9.3%	40000	12.1	14.5	25	750	570	13
600,000	495,000	62,250	300,000	220,000	105'-8	10'-9	16'-0	Yes	8	450A	Geared Side Rod	18/85	84,000 42,000	15.5% 7.8%	66,000 33,000	12.5% 6.4%	124,000	(1)8.3 (2)16.6	(1)8.3 (2)16.6	35	3200	2528 1264	14
576,000	432,000	72,250	258,400	157,600	76'-6	10'-1½	15'-6	Yes	4	451	Geared Side Rod	15/64	89,000	20.0%	69,000	16.6%	110,000	20.4	20.5	35	4800	4000	15
332,000	208,000	51,000	205,000	127,000	64'-11	10'-3½	14'-8½	No	2	315	Twin Gear	—	(1)21,300 (2)16,000	10.2% 8.5%	14,300 10,800	6.9% 5.2%	52,000	(1)30.8 (2)45.3	35.6 54.6	80	(1)760 (2)570	1364 1190	15a
343,000	193,000	48,250	194,000	149,000	64'-11	11'-2½	14'-8½	No	2	315A	"	—	(1)16,400	8.1%	10,500	5.0%	49,800	(1)35.6 (2)52.5	(1)37.6 (2)56.0	90	(1)730 (2)530	(1)1190 (2)1190	15b
195,140	195,140	48,785	100,000	95,140	38'-9	10'-7½	14'-4½	No	2	198	Twin Gear	—	19820	10.2%	13,240	6.8%	48,400	11.9	14.5	40	630	423	15c
240,000	160,000	40,000	158,900	81,100	55'-0	10'-1½	14'-3	Yes	4	GE 247A	Twin Gear	15/64	11,600	9.6%	12,720	9.2%	40000	40.5	41.25	82.2	(2)1680	1600	16a
200,000	200,000	50,000	118,800	81,200	39'-2"	10'-1½	14'-3	Yes	4	747A	"	15/64	30600	15.3%	28800	14.4%	50,000	20.8	21.0	36.8	(2)1680	1600	16b
283,800	203,800	51,450	149,800	117,000	52'-11	10'-7	14'-10	Yes	4	351	"	18/64	(1)5300 (2)4240	8.4%	(1)4240 (2)3390	6.9%	51,450	43.2	47.2	65	(2)2240	1800	16c
239,300	233,300	29,050	135,450	88,850	56'-2"	10'-6½	14'-10	Yes	6	350	Geared	15/64	(1)9,900 (2)7,900	12.6%	(1)7,600 (2)6,100	9.2%	58,575	21.4	23.4	42	(1)1640	1350	16d
226,000	226,000	37,670	140,000	86,000	49'-10	10'-0"	14'-10"	Yes	6	350B	"	16/63	(1)9,310 (2)7,450	12.4%	(1)7,450 (2)5,960	9.9%	56,000	22.6	24.6	40	1680	1350	17a
253,600	210,000	35,000	160,000	93,600	57'-4		14'-6	Yes	6		Geared	1/3	23,900	11.1%	16,080	7.7%	52,500	37.0	43.5	61.5	(2)2350	1810	17b
160,000	160,000	40,000	96,000	64,000	40'-3½		14'-5	No	4		"	1/1	15,400	9.35%	10,720	6.5%	40,000	37.0	43.5	56	(1)1500	1200	17c
136,000	136,000	34,000	86,000	50,000	40'-0"	10'-0"	14'-2"	No	4	350B	"	16/63	18,600	14.4%	(1)13,400	10.6	12.7	35	1520	450	17d

(1) Without Forced Ventilation. (2) Includes Steam Heating Equipment. (3) Full Field Ratings.
(4) Short Field Ratings (5) Max. T.E. 140,000 (6) Max. T.E. 69,000. (7) Max. T.E. 66,000
(8) Motors Series Parallel - 300° Ratings. (9) Max. T.E. at 19.7% adhesion limited by Motor Currents.

TABLE G

MULTIPLE-UNIT EQUIPMENT IN NORTH AMERICA—HEAVY SERVICE

Column No.	Railroad	Key No	Series No	No. in service	Year placed in service	System of traction	Contact Conductor Volts	Contact Conductor Type	Wheel diameter (inches)	Weight (lbs) Total	Trucks without motors	On drivers	Body without equipment	Equipment
1	Boston Elevated Ry Co	1-a	01-0150	120	1900	D C	600	Third rail	M-34, T-34	68,000	20,000	41,000	34,500	12,600
		1-b	0151-70	23	1903	D C	600	Third rail	"	68,000	20,030	45,300	34,670	12,500
		1-c	0171-219	45	1905	D C	600	Third rail	"	69,628	19,500	39,000	34,628	12,500
		1-d	0220-0330	30	1911	D C	600	Third rail	"	66,600	19,500	40,000	34,500	12,600
		1-e	0230-0295	55	1913	D C	600	Third rail	"	69,620	19,500	40,000	14,500	12,500
		1-f	0205-116	40	1917	D C	600	Third rail	"	65,383	18,100	38,200	35,183	12,500
		1-g	0600-0630	30	1911	D C	600	Third rail	"	80,000	22,000	46,000	48,000	16,000
		1-h	0630-50	20	1912-13	D C	600	Third rail	"	86,400	21,950	43,300	28,950	15,200
		1-i	0600-0604	35	1915	D C	600	Third rail	"	80,000	22,500	45,000	28,500	15,000
2	Brooklyn Rapid Transit Co	2-a		550	1903 & later	D C	600	Third rail	.....	.....	.....	.....	.....	.....
		2-b	.....	100	1902 & later	D. C.	600	Third rail	.....	.....	.....	.....	.....	.....
		2-c	2000-2899	900	1904 to 1921	D C.	600	Third rail	34	90,000	22,360	57,300	52,640	15,800
3	Canadian Nat'l Rys (Mt. Royal)	3	.....	5	1921	D C	2,400	Catenary	36	120,000	30,000	120,000	51,000	30,000
4	Chicago Elevated Ry Co	4-a	.....	20	1902	D C	600	Third rail	33	60,500	22,000	41,000	31,000	13,500
		4-b	.....	150	1905	D C	600	Third rail	34	50,500	10,000	35,600	26,000	13,500
		4-c	.....	103	..	D C	600	Third rail	34	.....	.....	.....	.....	.....
		4-d	.....	60	1912	D C	600	Third rail	34	68,500	20,000	47,000	37,500	12,100
		4-e	.....	19	1914	D C	600	Third rail	34	70,903	19,000	42,000	35,500	14,000
5	Chicago, North Shore & Milwaukee R R	5-a	.....	6	1908	D C	600	Dir. Susp	36	67,000	15,000	67,000	32,000	17,000
		5-b	.....	32	1905-10	D C	600	Dir. Susp	36	76,000	18,050	70,000	40,000	18,000
		5-c	.....	21	1915-21	D C	600	Dir. Susp	36	93,000	22,000	93,000	42,000	19,000
		5-d	.....	45	1915-21	D C.	600	Dir Susp	36	100,000 93,000 100,000	32,930	100,000 93,000 100,000	40,000 .000	10,000
6	Erie R R. Co	6-a	.....	6	1907-12	A C.	11,000	Catenary	36	95,000		95,000		18,000
		6-b	.....	..	..	..	..	..	..	117,000	35,030	117,000	49,000	13,000
7	Hudson & Manhattan R R	7-a	Class A	50	1907	D. C.	600	Third rail	M-348, T-30	74,550	23,750	47,000	35,170	15,630
		7-b	Class B	50	1909	D C	600	Third rail	"	69,620	21,800	43,800	32,100	15,830
		7-c	Class C	50	1910	D C	600	Third rail	"	69,620	21,850	43,500	32,150	15,830
		7-d	Class D	96	1911	D. C	600	Third rail	M-36, T-33	73,000	23,000	46,000	33,600	16,000
		7-e	Class E	25	1921	D C.	600	Third rail	M-318, T-30	73,500	24,340	46,700	37,054	12,100
8	Interborough Rapid Transit Co	8-b	.....	273	1904	D. C.	600	Third rail	M 348 T-31	85,500	23,000	51,000	47,000	14,600
		8-j	.....	88	1910	D C	600	Third rail	"	59,300	17,700	36,000	26,900	14,600
		8-k	.....	66	1910	D C	600	Third rail	"	59,200	17,700	36,000	26,900	14,600
		8-l	.....	6	1915	D C	600	Third rail	"	73,000	23,000	46,000	33,800	16,200
		8-m	320	320	1915	D C	600	Third rail	"	71,800	19,300	39,800	32,100	11,500
		8-v	100	100	1917	D C	600	Third rail	"	75,500	23,000	45,000	30,000	15,500
		8-a	828	828	1900-3	D C	600	Third rail	"	55,120	20,000	31,500	24,620	11,000
		8-c	.....	200	1904	D C	600	Third rail	"	58,500	16,300	35,000	27,700	14,500
		8-d	.....	277	1904	D C	600	Third rail	"	65,460	23,000	51,000	41,000	14,600
		8-e	.....	91	1907	D C	600	Third rail	"	50,100	23,940	35,700	21,750	13,500
		8-f	.....	40	1907	D C	600	Third rail	"	83,300	25,100	49,800	44,900	13,500
		8-g	.....	190	1908	D C	600	Third rail	"	81,200	25,100	49,800	44,000	13,500
		8-h	.....	88	1910	D C	600	Third rail	"	59,100	17,700	36,000	26,900	14,500
		8-i	.....	60	1910	D C	600	Third rail	"	59,150	17,700	36,000	26,900	14,500
		8-n	.....	0	1915	D C	600	Third rail	"	70,960	27,600	45,000	33,100	16,180
		8-o	.....	0	1915	D C	600	Third rail	"	73,000	23,000	46,000	33,820	16,180
		8-p	.....	161	1915	D C	600	Third rail	"	75,000	27,000	45,000	37,500	10,500
		8-q	.....	330	1915	D C	600	Third rail	"	73,788	19,200	39,780	43,084	11,500
		8-r	.....	103	1915	D C	600	Third rail	"	75,500	27,000	45,000	37,500	13,500
		8-s	.....	74	1915	D C	600	Third rail	"	71,000	23,000	40,740	37,500	10,500
		8-t	.....	108	1915	D C	600	Third rail	"	75,500	23,000	45,350	30,000	13,500
		8-u	.....	160	1917	D. C	600	Third rail	"	75,500	23,000	45,350	30,000	13,500
* 9	Long Island R R. Co	9-a	.....	135	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
		9-b	.....	300	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10	Metropolitan West Side Elevated Ry (Chicago & Oak Park)	10-a	.....	14	1904	D C.	600	Third rail	34	65,000	16,000	38,600	37,000	12,000
		10-b	.....	77	1908	D. C.	600	Third rail	34	55,000 to 70,000	22,000	38,500 to 41,000	26,600 to 31,600	16,400
		10-c	.....	36	1904	D C.	600	Third rail	34	69,500	22,000	41,000	31,000	
		10-d	.....	61	1914-15	D C.	600	Third rail	34	70,000	19,000	42,000	33,400	14,600
11	New York Central R R	11-a	4100-123	122	1907	D. C.	600	Third rail	M-36, T-33	107,500	25,150	61,350	63,800	18,700
		11-b	4123	1	1907	D C	600	Third rail	"	112,100	25,160	61,600	68,356	18,700
		11-c	4155-72	18	1907	D C	600	Third rail	"	119,000	26,303	64,700	74,000	18,704
		11-d	4173	1	1907	D C	600	Third rail	"	113,303	24,303	61,850	67,300	18,703
		11-e	4125-52	30	1907	D C	600	Third rail	"	114,000	26,300	61,300	69,000	18,700
		11-n	4174-07	10	1913	D C	600	Third rail	"	117,500	25,150	65,700	72,000	18,700
		11-f	4350-51	6	1907-10	D C	600	Third rail	"	113,500	24,150	63,000	60,850	18,700
		11-j	4356-63	6	1913	D C	600	Third rail	"	116,000	26,350	64,000	71,300	18,700
		11-k	4193-202	17	1917	D C	600	Third rail	"	132,200	33,600	73,100	84,850	25,000
		11-l	4305-32	33	1918-21	D C	600	Third rail	"	129,000	33,800	71,600	79,500	25,100
		11-g	4304-07	4	1910	D C	600	Third rail	"	119,470	25,150	67,200	75,550	18,700
		11-h	4308-06	3	1910-18	D C	600	Third rail	"	128,200	26,000	69,150	74,000	18,700
12	New York, New Haven & Hartford	12-d	4010	1	1914	*A C	11,000	Catenary	36	150,500	37,700	150,500	80,673	20,000
		12-b	4011	1	1911	*A C	11,000	Catenary	36	130,700	23,013	13,000	60,083	16,700
		12-a	4030-33	4	1900	D. C. A C	600 11,000	Third rail and Cat	42	173,500	41,000	173,500	95,700	60,800
		13-c	4022-27	4	1912	"	"	"	42	171,100	40,500	171,100	60,000	61,600
		13-d	4028-29	2	1914	"	"	"	42	170,000	40,500	170,000	60,000	61,500
		12-f	4060-61	2	1915	*A C	11,000	Catenary	42	160,000	40,500	160,000	68,500	60,000
		12-g	4062-63	2	1916	*A C	11,000	Catenary	42	170,000	40,430	170,000	65,190	64,180
		12-h	....	6	1921	A C.-D C	600-11,000	Third rail and Catry	42	176,000	40,500	176,000	69,000	56,500
		12-i	....	2	1921	"	"	"	42	176,000	40,500	176,000	69,000	56,500
13	New York, Westchester & Boston	13	101-140	40	1912 & 1913	A C.	11,000	Catenary	M-32, T-30	120,000	29,200	71,570	.....	.....
14	New York Municipal Ry	14	.....	900	1914-20	D C.	600	Third rail	M-34, T-31	90,600	23,560	57,390	52,840	15,800
15	Northwestern Elevated R R	15-a	.....	192	1900-05	D C.	600	Third rail	34	65,000 to 69,000	18,300	40,000	30,200 to 31,550	16,500
		15-b	.....	20	1908	D C	600	Third rail	34	60,000 69,000	20,050 20,950	41,000 41,000	31,550 31,550	16,500
		15-c	.....	20	1914	D C	600	Third rail	34	68,500	20,950	41,000	37,300	
		15-d	.....	43	1914-15	D C	600	Third rail	34	70,000	19,950	42,000	35,400	14,600
		15-e	.....	10	1914-15	D C	600	Third rail	34	70,000	19,000	42,000	35,400	
		15-a	101-200	0	1910	D. C.	600	Third rail	34	110,350	26,000	63,550	60,000	24,350
		15-b	4513-12	2	1910	D C	600	Third rail	34	108,550	26,000	61,300	58,000	23,250
		15-c	201-83	83	1915	A C.	11,000	Catenary	.....	118,000	31,800	70,000	60,000	26,000
		15-d	4518-51	9	1915	A C.	11,000	Catenary	.....	116,000	31,800	70,000	58,000	25,800
		15-e	4553-57	2	1915	A C.	11,000	Catenary	.....	121,600	31,800	70,100	63,000	26,800
		15-f	5400-83	20	1915	A C.	11,000	Catenary	.....	118,000	31,800	70,000	60,000	26,800
		15-g	5000-20	2	1917	A C.	11,000	Catenary	.....	123,600	31,800	68,100	55,000	26,800
17	Philadelphia Rapid Transit Co	17-a	.....	40	1907	D C	600	Third rail	33	71,500	23,000	46,300	34,150	13,850
		17-b	.....	40	1907	D C	600	Third rail	33	76,000	28,500	49,400	33,650	13,750
		17-c	.....	16	1909	D C	600	Third rail	34	72,000	23,000	46,300	35,150	13,850
		17-d	.....	4	1909	D C	600	Third rail	34	76,000	28,500	49,300	33,650	13,850
		17-e	.....	63	1911	D C	600	Third rail	34	70,500	23,000	45,800	33,650	13,850
		17-f	.....	50	1911	D C	600	Third rail	33	72,000	23,000	46,300	34,300	13,700
		17-g	.....	50	1921	D C.	600	Third rail	33	72,500	.....	.....	.....	.....
18	Southern Pacific Co. (O. A. & B. Div.)	18	.....	31	1921	D. C.	1,200	Catenary	36	199,400	74,250	199,400	61,250	23,000
19	South Side Elevated R R	18-a	.....	140	1893	D C.	600	Third rail	34	114,000 52,814	15,500	114,000 31,500	60,120 27,000	10,400
		19-b	.....	70	1900-3	D C	600	Third rail	34	55,000	17,500	32,000	24,000	12,000
		19-c	.....	150	1903	D C	600	Third rail	34	59,500	19,000	35,000	..	..
		19-d	61	61	1914-15	D C	600	Third rail	34	70,000	19,000	42,000	35,400	14,600
20	West Jersey & Sea Shore R. R	20-a	6191-62	60	1900	D. C.	625	Third rail, Dir. Susp	M-36, T-33	80,000	25,045	52,800	40,495	16,550
		20-d	6163-70	17	1907	D C.	675	"	"	94,700	25,900	56,300	52,250	16,550
		20-e	6135-36	2	1907	D C.	675	"	"	94,000	25,900	55,900	51,550	16,550
		20-g	6180-93	13	1913	D C.	675	"	36	105,000	29,100	61,400	56,000	16,000
		20-h	6137-38	2	1912	D C.	675	"	36	104,000	29,100	61,400	58,000	16,000
		20-b	6455-1-8	3	1900	D. C.	675	"	M-36, T-33	88,000	25,045	52,800	46,403	16,550
		20-c	6431-36	9	1906-9	D. C.	675	"	"	92,000	25,900	54,875	49,550	16,550
		20-f	6431-6437	1	1911	D. C.	675	"	36	101,000	29,100	71,933	55,000	16,000

* Single P. H

(Continued on page 321)

TABLE G (Continued)

MULTIPLE-UNIT EQUIPMENT IN NORTH AMERICA—HEAVY SERVICE

Company No.	Railroad	Dimensions			Wheel base		Motors		Gear ratio	One hour rating forced ventilation			Seating capacity	Key No.
		Length over all	Width over all	Height top rail to highest point trolley down	Rigid	Total	No.	Type		Total T E (lbs.)	Speed M P H	H P each motor		
1	Boston Elevated Ry. Co.	46'-7½"	8'-9½"	13'-6½"	6'-0"	38'-3½"	2	W-301	18 59	6,000	22	175	48	1-a
		46'-7½"	8'-9½"	13'-6½"	6'-0"	38'-3½"	2	GE-250 B	60 17	4 775	18	120	48	1-b
		46'-7½"	8'-9½"	12'-6½"	M-6'-1"	38'-3"	2	GE-250 B	60 17	4 775	18	120	48	1-c
					T-6'-0"									
		46'-7½"	8'-9½"	13'-6½"	6'-0"	38'-3½"	2	W-301	18 59	6,000	22	175	48	1-d
		46'-7½"	8'-9½"	12'-6½"	6'-0"	38'-3½"	2	W-301	18 59	6,000	22	175	48	1-e
		46'-7½"	8'-9½"	12'-6½"	M-6'-1"	38'-3½"	2	GE-250	60 17	4 775	18	120	48	1-f
					T-6'-0"									
		60'-6¼"	9'-0½"	13'-5½"	M-7'-0"	52'-6"	2	W-300	20 63	8,000	21	220	72	2-g
		60'-6¼"	9'-0½"	12'-5½"	T-6'-0"	52'-6"	2	GE-212	63 20	8,000	18	225	72	2-h
		60'-6¼"	9'-0"	12'-8½"		51'-0"	2	W-577	20 63	6,900	21.5	200	72	2-i
							2	W-50				140		2-j
							2	W-300				220		2-k
		63'-0"	10'-0"	13'-3"	6'-8"	50'-3"	2	GE-228						2-l
3	Canadian Nat'l Rys. (Mt. Royal)	63'-0"	10'-0"	13'-0"	7'-0"	51'-0"	4	GE-239	66 24	9,000	23	150	68	3
8	Chicago Elevated Ry. Co.	43'-0½"	8'-8"	12'-10"	6'-0"	43'-0"	2	W-100				18	48	4-a
		43'-3"	8'-8"	12'-8"	6'-0"	40'-1"	2	W-120	17 58			100	52	4-b
							2	W-114				175		4-
		46'-7½"	8'-8"	13'-5"	6'-0"	38'-8"	2	W-303				120	48	4-
		48'-0½"	8'-8"	13'-3½"	6'-3"	40'-0"	2	W-567	17 60	8,200	20	175	52	4-
5	Chicago, North Shore & Milwaukee R. R.	46'-0"	9'-0½"	13'-7½"	6'-0"	31'-10"	4	GE-74	67 22	2 940	20 6	65	46	5-
		52'-3"	8'-8½"	13'-10 3/16"	6'-0"	35'-10"	4	GE-73	52 22	3,200	23	75	54	5-
		56'-1"	8'-8"	12'-10½"	7'-0"	39'-8"	4	W-577	54 22	5,620	41	140	56	5-
		56'-1"	8'-8"	13'-10½"	7'-0"	39'-8"	4	W-557	23 64	7,800	37	140	56	5-
6	Erie R. R. Co.	53'-3"	8'-6"	13'-0"	6'-8"	40'-0"	4	W-132	20 63				70	6-
		63'-3"	9'-0"	10'-11"	7'-0"	49'-0"	4	W-132-C	20 63					6-
7	Hudson & Manhattan R. R.	48'-5"	8'-11 3/16"	12'-0"	M-6'-6"	39'-5½"	2	GE-216	62 19	7,200	18	150	44	7-
					T-3'-0"									
		48'-5"	8'-11½"	11'-8 7/16"	"	39'-5½"	2	GE-216	62 19	7,200	18	150	44	7-b
		48'-5"	8'-11½"	11'-8 7/16"	"	39'-5½"	2	GE-216	62 19	7,200	18	150	44	7-c
		48'-3½"	8'-8½"	11'-8½"	7'-0"	40'-0"	2	GE-212-C	53 22	6,740	37	225	44	7-c
		51'-3½"	8'-8½"	12'-9 7/8"	M-6'-6"	39'-5½"	2	GE-250	60 17	4 775	18	120	44	7 f
					T-3'-0"									
8	Interborough Rapid Transit Co.	51'-0½"	9'-0½"	12'-0"	M-6'-8"	42'-3"	2	W-86	19 83	7,300	19 5	300		8-f
					T-3'-0"									
		47'-0½"	8'-0½"	13'-4"	M-6'-0"	36'-8"	2	W-300	20 63	8,000	21	220	48	8-j
					T-3'-0"									
		47'-0½"	8'-0½"	13'-4"	"	38'-8"	2	W-302	16 61	5,800	18	140	48	8-k
		51'-0½"	9'-0½"	12'-0"	M-6'-8"	42'-3"	2	W-302	17 60	5,400	19 5	140	48	8-l
					T-3'-0"									
		51'-0½"	9'-0½"	12'-0"	"	42'-3"	2	W-333	18 61	4,200	21	115	48	8-i
		51'-0½"	9'-0½"	12'-0"	"	42'-3"	2	W-577	21 62	6,500	33	200	48	8-i
		47'-0½"	8'-0½"	13'-3½"	M-6'-0"	38'-8"	2	GE-66A	61 10	6,600	14 5	125		8 c
					T-3'-0"									
		47'-0½"	8'-0½"	13'-3½"	"	38'-8"	2	GE-69-B	63 20	8,100	18 4	200		8-i
		51'-0½"	9'-0½"	12'-0"	M-6'-8"	42'-3"	2	W-86-B	63 19					8-i
					T-3'-0"									
		47'-0½"	8'-0½"	13'-3½"	M-6'-0"	36'-8"	2	GE-211-A	61 16	5,400	13 6	160	48	8 e
					T-3'-0"									
		47'-0½"	8'-0½"	13'-3½"	"	36'-8"	3	GE-212-A	63 20	8 760	20 4	235	48	8-f
		51'-0½"	9'-0½"	12'-0"	M-6'-8"	42'-3"	3	GE-212-A	63 20	8,760	20 4	235		8-g
					T-3'-0"									
		47'-0½"	8'-0½"	13'-3½"	M-6'-0"	38'-8"	2	W-300	84 20				48	8-h
					T-3'-0"									
		47'-6½"	8'-0½"	13'-3½"	"	38'-8"	3	W-302	81 16					8-i
		51'-0½"	9'-0½"	12'-0"	M-6'-8"	42'-3"	3	GE-240-C	60 16	3,130	33 7	94	48	8-d
					T-3'-0"									
		51'-0½"	9'-0½"	12'-0"	"	42'-3"	2	W-302-F	60 17				48	8-o
		51'-0½"	9'-0½"	12'-0"	"	42'-3"	2	GE-239-A	61 16	4,040	32 6	120		8-p
		51'-0½"	9'-0½"	13'-0"	"	42'-3"	2	W-333	61 16					8-q
		51'-0½"	9'-0½"	13'-0"	"	42'-3"	3	GE-260-A	62 21	6,350	23	195	48	8-r
		51'-0½"	9'-0½"	13'-0"	"	42'-3"	3	GE-239-A	61 18	4,040	32 6	120		8 s
		51'-0½"	9'-0½"	12'-0"	"	42'-3"	3	GE-260-A	62 21	6,350	33	195	48	8-t
		51'-0½"	9'-0½"	12'-0"	"	42'-3"	3	W-577	62 21					8-u
9	Long Island R. R. Co.						2	W-113				210		9-a
							2	W-308				210		9-b
10	Metropolitan West Side Elevated Ry. (Chicago and Oak Park).	47'-0½"	8'-0"	12'-10"	5'-9"	36'-7"	2	GE-2,000	3 17	4,000	21	135	40	10-a
		47'-0½"	8'-2"	13'-10"	6'-0"	39'-7"	3	GE-55	59 18	7,000	18	160	48	10-b
		47'-0½"	8'-2"	13'-10"	6'-0"	41'-1"	2	W-103	3 17				48	10-c
11	New York Central R. R.	62'-3"	9'-0"	12'-11"	6'-0"	40'-0"	2	GE-243	60 17	8,400	18	155	52	10-d
		62'-3"	9'-0"	12'-10"	7'-0"	45'-0"	2	GE-60-C	40 26	5,700	37	195	70	11-a
		62'-3"	9'-0"	12'-10"	7'-0"	45'-0"	2	GE-69-C	40 26	5,700	37	195	70	11-b
		62'-3"	9'-0"	12'-10"	7'-0"	45'-0"	2	GE-69-C	40 26	5,700	37	195	70	11-c
		62'-3"	9'-0"	13'-10"	7'-0"	45'-0"	3	GE-69-C	40 26	5,700	37	195	70	11-d
		62'-3"	9'-0"	12'-10"	7'-0"	45'-0"	3	GE-69-C	40 26	5,700	37	195	70	11-e
		62'-3"	9'-0"	13'-10"	7'-0"	45'-0"	3	GE-60-C	40 26	5,700	37	195	74	11-i
		62'-3"	9'-0"	13'-10"	7'-0"	45'-0"	3	GE-69-C	40 26	5,700	37	195	42	11-f
		62'-3"	9'-0"	12'-10"	7'-0"	45'-0"	3	GE-69-C	40 26	5,700	37	195	40	11-g
		60'-5"	9'-0"	13'-5"	8'-0"	52'-10"	2	GE-260-B	51 18	6,900	21	195	82	11-k
		60'-5"	9'-0"	13'-5"	8'-0"	52'-10"	3	GE-260-B	51 18	8,000	34	195	82	11-l
		61'-2"	9'-0"	14'-10"	7'-0"	45'-0"	2	GE-69-C	40 26	5,700	37	195	0	11-e
		61'-2"	9'-0"	14'-10"	7'-0"	45'-0"	2	GE-69-C	40 26	5,700	37	195	0	11-h
12	New York, New Haven & Hartford	70'-10½"	9'-7½"	13'-8½"	8'-0"	52'-7"	4	GE-A 613-B	67 23	8,800	33	350	76	12-a
		70'-10½"	9'-7½"	14'-3"	8'-0"	55'-7½"	4	GE-A 613-B	67 23	8,800	33	350	76	12-b
		70'-10½"	9'-7½"	14'-3"	8'-0"	55'-7½"	4	W-156	33 76				76	12-c
		70'-10½"	9'-7½"	14'-3"	8'-0"	55'-7½"	4	W-409-D	37 73				76	12-d
		71'-11"	9'-8½"	14'-3"	8'-0"	55'-7½"	4	W-409-D	37 73				76	12-e
		71'-11"	9'-8½"	14'-3"	8'-0"	55'-7½"	4	W-413	33 58				76	12-f
		71'-11"	9'-8½"	14'-5"	8'-0"	55'-7½"	4	GEA 674-D	77 28	10,120	30	450	76	12-g
		71'-11"	9'-8½"	14'-5"	8'-0"	55'-7½"	4	W-409-D	37 73				76	12-h
		75'-11½"	9'-8½"	15'-3"	8'-0"	55'-7½"	4	W-417	18 61				76	12-i
13	New York, Westchester & Boston	67'-0"	10'-0"	14'-11"	8'-0"	55'-7½"	4	W-409-B	35 68				78	13
14	New York Municipal Ry.	67'-0"	10'-0"	14'-11"	8'-0"	55'-7½"	4	W-248	35 68	5,300	23 5	200	90	14
15	Northwestern Elevated R. R.	46'-7½"	8'-8"	13'-5"	6'-0"	38' 5"	2	GE-55	58 18	7,000	18	160	48	15-b
		46'-7½"	8'-8"	13'-5"	6'-0"	38'-8"	2	GE-211-B	58 18	7,000	18	160	48	15-b
		46'-7½"	8'-8"	13'-5"	6'-0"	38'-8"	2	W-301	3 18				48	15-c
		48'-0½"	8'-8"	13'-3½"	6'-8"	40'-0"	3	GE-243	60 17	8,400	19	155	52	15-d
		48'-0½"	8'-8"	13'-3½"	6'-8"	40'-0"	3	W-567	60 17				52	15-e
16	Pennsylvania R. R. (New York)	64'-0½"	9'-11½"	13'-3½"	7'-0"	46'-0"	2	W-308	35 48	*1,700	*33	*225	72	16-a
		64'-0½"	9'-11½"	13'-3½"	7'-0"	46'-0"	2	W-303	35 48	*1,700	*33	*225	52	16-b
	Pennsylvania R. R. (Philadelphia)	64'-0½"	9'-11½"	15'-0½"	M8'-8"	48'-1"	2	W-412-A	24 55	3,800	44 5	225	72	16-c
					T8'-0"									
		64'-0½"	9'-11½"	15'-0½"	M8'-8"	48'-1"	2	W-412-A	84 58	3,800	44.5	225	52	16-d
					T8'-0"									
		64'-0½"	9'-11½"	15'-0½"	M8'-8"	48'-1"	2	W-412-A	24 55	3,800	44 5	225	—	16-e
					T8'-0"									
		64'-0½"	9'-11½"	15'-0½"	M8'-8"	48'-1"	2	W-412-A	24 55	3,800	44.5	225	72	16-f
					T8'-0"									
		64'-0½"	9'-11½"	15'-0½"	M8'-8"	48'-1"	2	W-412-A	24 55	3,800	44 5	225	—	16-g
					T8'-0"									
17	Philadelphia Rapid Transit Co.	49'-7"	8'-8"	12'-6"	6'-7"	40'-2"	3	GE-66	61 17	5,300	18	125	48	17-a
		49'-7"	8'-8"	12'-6"	6'-9"	40'-2"	3	GE-66	61 17	*5,300	18	125	48	17-b
		49'-7"	8'-8"	12'-6"	6'-9"	40'-2"	3	GE-68	61 17	5,200	18	125	48	17-c
		49'-7"	8'-8"	12'-6"	6'-9"	40'-2"	3	GE-66	61 17	5,200	18	125	48	17-d
		49'-7"	8'-8"	12'-6"	6'-9"	40'-2"	3	GE-66	61 17	5,200	18	125	48	17-e
		49'-7"	8'-3"	12'-6"	6'-8"	40'-2"	3	GE-222	61 17	5,000	18	140	48	17-f
18	Southern Pacific Co. (O. A. & B. Division)	72'-10½"	10'-0"	15'-1"	7'-0"	52'-0"	4	GE-259	16 81					17-g
19	South Side Elevated R. R.	47'-1"	8'-8"	12'-8"	5'-6"	38'-2"	2	GE-207	64 17	11,680	18	240	110	18
		47'-1"	8'-8"	12'-8"	5'-6"	38'-2"	2	GE-57-B	3 05	3,450	18	50	46	19-a
		49'-7"	8'-8"	12'-8"	6'-0"	40'-2"	2	GE-73-A	51 68	3,500	18	75	44	19-b
		47'-1"	8'-8"	12'-8"	6'-1"	40'-1"	2	W-121	3 41				52	19-c
		48'-0½"	8'-8"	13'-3½"	6'-8"	40'-0"	2	GE-243	60 17	8,400	19	155	52	19-d
		55'-2½"	10'-0½"	15'-2 5/16"	7'-0"	40'-0"	2	GE-69-C	40 26	4,600	32 4	200	58	20-a
		55'-2½"	10'-0½"	15'-2 5/16"	M-7'-3",	40'-11½"	3	GE-69-C	40 26	4,600	32 4	200	58	20-d
					T-7'-0"									
		55'-2½"	10'-0½"	15'-3 5/16"	"	40'-11½"	3	GE-69-C	40 26	4,600	32 4	200	58	20-e
		64'-0½"	9'-11½"	15'-1"	8'-0"	47'-0"	2	GE-212-F	52 23	6,000	30 3	335	72	20-g
		64'-0½"	9'-11½"	15'-1"	8'-0"	47'-0"	2	GE-212-F	52 23	6,000	30 3	335	72	20-h
		55'-2½"	10'-0½"	15'-2 5/16"	7'-0"	40'-0"	3	GE-69-C	40 26	4,600	32 4	200	0	20-b
		55'-2½"	10'-0½"	15'-2 5/16"	M-7'-3",	40'-11½"	3	GE-69-C	40 26	4,600	32 4	200	0	20-c
					T-7'-0"									
		64'-0½"	9'-11½"	15'-1"	8'-0"	47'-0"	3	GE-212-F	52 23	6,000	30 3	335	0	20-f

* Natural Ventilation.

TABLE H

Power Transmission

Railroad	Number circuits	Conductors: Size	Conductors: Material	Conductors: Spacing	Conductors: Av. span	Insulators: Make	Insulators: Type	Poles, material	Voltage	Current	Phases	Cycles
*Baltimore & Ohio	..	.....	.....	.....	.....	.....	.....	.....	.....	...	...	..
*Boston & Maine	2	4/0	Copper	.....	100 ft.	Locke	603, 80,405	Wood	11,000	a.c.	1 ϕ	25
*Butte, Anaconda & Pacific	..	.....	.....	.....	.....	.....	.....	.....	.....	...	...	..
*[1]Chicago, Milwau. & St. P.	1	2/0	Copper	Varies	350 ft.	Various	Suspension	Wood	100,000	a.c.	3 ϕ	60
*[2]Chicago, Milwau. & St. P.	1	2/0 & 1/0	Copper	Varies	350 ft.	Various	Suspension	Wood	100,000	a.c.	3 ϕ	60
*Erie	..	.....	.....	.....	.....	.....	.....	.....	60,000	a.c.	3 ϕ	25
*Grand Trunk	..	4/0 & 300,000 c.m.	Copper	.....	.....	.....	.....	.....	.....	...	...	..
*Great Northern	2	No. 2	Copper	5′ 10″ hor. / 3′ 6″ vert.	.....	.....	.....	Wood	33,000	a.c.	3 ϕ	25
*Long Island	1-10	2/0 / 250,000 c.m. / 350,000 c.m.	Copper	24″	150 ft.	Various	Pin	Steel & wood	11,000	a.c.	3 ϕ	25
Michigan Central	..	.....	.....	.....	.....	.....	.....	.....	.....	...	...	..
N. Y. C. & Hudson River	..	.....	.....	.....	.....	.....	.....	.....	.....	...	...	..
New York Connecting	..	.....	.....	.....	.....	.....	.....	.....	.....	...	...	..
*N. Y. N. H. & Hartford	4	4/0	Copper	.....	300 ft.	Ohio Brass	Pin & Susp'n	Steel bridges	22,000	a.c.	1 ϕ	25
*N. Y. W. Chester & Boston	4	4/0	Copper	3′ 1″ hor. / 5′ 0″ vert.	300-400 ft.	.....	.....	Steel bridges	22,000	a.c.	1 ϕ	25
*Norfolk & Western	2	2/0	Copper	.....	300 ft.	.....	.....	Steel bridges	44,000	a.c.	1 ϕ	25
*Oregon Electric	1	105,530 c.m.	Aluminum	6′ 0″ $\triangle$	150 ft.	Thomas	Pin	Wood	60.000	a.c.	1 ϕ	33
*[3]Pennsylvania System	..	250,000 c.m.	Copper	3 cond. lead	Underground	.....	.....	.....	11,000	a.c.	3 ϕ	25
*[4]Pennsylvania System	4	2/0	Copper	5′ 0″ hor. / 3′ 6″ vert.	.....	.....	.....	.....	44,000	a.c.	2-1 ϕ	25
[5]Pennsylvania System	2	No. 1	Copper	42″ $\triangle$	125 ft.	.....	.....	Wood	33,000	a.c.	3 ϕ	25
South'n Pac. Portland Div.	2	1/0	Copper	3′ 0″	150 ft.	Ohio Brass	9,410	Steel & wood	13,200	a.c.	3 ϕ	60
	1	No. 4	Copper	6′ 0″	.....	Locke	341	.....	55,000	a.c.	3 ϕ	60
Southern Pacific (Oakland Alameda & B)	2	1/0	Copper	3′ 0″ hor.	.....	.....	.....	Steel	13,200	a.c.	3 ϕ	25
Spokane & Inland	..	.....	.....	.....	.....	.....	.....	.....	.....	...	...	..
*Visalia Electric	2	4	Copper	.....	120 ft.	.....	.....	Trolley poles	11,000	a.c.	1 ϕ	15
*Canadian National	5	4/0	Copper	.....	150 ft.	Locke	408	Cedar	2,400	d.c.	...	..
Paulista	2	1/0	Copper	.....	.....	.....	.....	H poles wood	88,000	a.c.	3 ϕ	60

*Data given in 1920 report corrected and extended by railroad.
[1]Harlowton—Avery.
[2]Othello—Seattle—Tacoma.
[3]Manhattan Transfer through New York station to Sunnyside yards.
[4]Broad Street station, Philadelphia, to Paoli and Chestnut Hill.
[5]Camden to Atlantic City and Millville.

See also Tables C to E on pages 312 to 317.

TABLE K

Railroad	Termini	Route, miles	System of electrification	No. of locomotives	No. of motor cars	No. of trailer cars	Date installed
			ARGENTINE				
Central Argentina Ry.	Retiro–Tigre	50	D.C. — 800 v.— 3d rail	.....	67	50	.....
			BRAZIL				
Paulista Ry.	Jundiahy–Campinas	28	D.C.— 3,000 v.— Catenary	16	.....	.....	1921
			CHILE				
Chile State Rys.	Valparaiso–Santiago–Los Andes.	144	D.C.— 3,000 v.— Catenary	39	.....	.....	Under construction
Bethlehem Chile Iron Mines Co.	Tofo–Cruz-Grande	15	D.C.— 2,400 v.— Catenary	3	.....	.....	1920
			AUSTRALIA				
Victorian Rys.	Melbourne–Suburban points	143	D. C.—1,500 v.—Catenary	.....	400	400	1919
			ENGLAND				
Midland Ry.	Lancaster–Heysham–Morecambe	9.7	A.C.— 1 ϕ — 25~ — 6,600 v.— Catenary.	.....	3	6	1 90
London, Brighton and South Coast Ry.	Victoria–London Bridge	8.7	A.C.— 1 ϕ — 25~ — 6,600 v.— Catenary.	.....	50	82	1909
	Battersea Park and Peckham	13.6	A.C.— 1 ϕ — 25~ — 6,600 v.— Catenary.	.....			1911
	Rye to Crystal Palace						
Lancashire and Yorkshire Ry.	Liverpool (Exchange Sta.) to Crossens.		D.C.— 600 v.— 3d rail (4th rail return).	.....			1904
	Liverpool (Dingle) to Crossens via Liverpool.		" " " "	.....			1906
	Seaforth and Bankhall to Aintree	37.25	" " " "	.....	70	84	1906
	Aintree to Maghull		" " " "	.....			1906
	Maghull to Town Green		" " " "	.....			1911
	Town Green to Armskirk		" " " "	.....			1913
	Manchester–Burg	8.1	D.C.— 1,200 v.— 3d rail	.....	.....	.....	1916
North Eastern Ry.	Newcastle-on-Tyne–Benton–Tynemouth.	29.5	D.C.— 600 v.— 3d rail	2 (frt.)	65	44	1904
	Shildon–Newport	18.0	D.C.— 1,500 v.— Catenary	10	.....	.....	1916
Great Western Ry.	Bishops Road–Westboune Park	4.1	D.C.— 600 v.— 3d rail (4th rail return).	.....	40	80	1906
Metropolitan Ry.	London and Suburban points	.....	D.C.— 600 v.— 3d rail (4th rail return).	.....	20	.....	1903

See also Tables K-1 and K-2 on pages 324 to 327.

TABLE K-1

Railroad	Termini	Route, miles	System of electrification	No. of locomotives	No. of motor cars	No. of trailer cars	Date installed
FRANCE							
Orleans Co.	Paris (Quai d'Orsay to Austerlitz)	2.5	D.C.— 600 v.— 3d rail	18	7	.....	1900
Orleans Co.	Paris (Austerlitz) to Jurisy	11.9	D.C.— 600 v.— 3d rail				1904
Ouest Co. ((State repurchased in 1908).	Invalides Sta. Paris–Versailles	11.2	D.C.— 600 v.— 3d rail	.....	44	.....	1901
Paris–Lyons–Mediterranean	Cannes–Grasse	.....	A.C.— 1 ϕ — 12,000 v.— 25~	1	.....	.....	1911
Midi Co.	Montagne de Villefranche–Perpignan.	29.0	A.C.— 1 ϕ — 16⅔~ — 12,000 v. Catenary.	.....	.....	.....	1911–13
	Pau–Pierrefitte–Tarbes	36.6	" " " "	.....	.....	.....	
	Tarbes Bagneres de Bigorre, Arreau, Bagneres de Luchon.	125.9	" " " "	.....	.....	.....	
French State Ry.	St. Georges de Commiers–La Muve.	19.3	D.C.— 2,400 v.— Catenary	.....	.....	.....	1904
SPAIN							
Southern Ry. of Spain	Gergal–Sante Fe	14	A.C.— 3 ϕ — 25~ — 5,200 v.	5	.....	.....	1911
Northern Ry. of Spain	Budonzo–Ujo (Pajaves Grade)	40	D.C.— 3,000 v.	12	.....	.....	Under construction
Pamplona–Sanguesa Ry	Pamplona–Aoiz–Sanguesa	39±	A.C.— 1 ϕ — 25~ — 6,600 & 600 v.— Catenary.	.....	.....	.....	.....
GERMANY							
Prussian State Ry.	Dessau–Bitterfeld	16	A.C.— 1 ϕ — 15~ — 10,000 v.— Catenary.	11	.....	.....	1911
	Halle–Leipzig–Bitterfeld	95					
	Dessau–Magdeburg. (Continuation of Dessau–Bitterfeld line).		" " " "	.....	.....	.....	.....
(Silesia)	Lauban–Königszett and Branches	170	A.C.— 1 ϕ — 16⅔~ — 15,000 v. — Catenary.	25	.....	.....	1914
Mittenwald Ry.	(See Austria.)						
Wiesemthal Ry.	Basel–Schopfheim–Säckingen–Zell.	31	A.C.— 1 ϕ — 15~ — 10,000 v. — Catenary.	13	.....	.....	1912

AUSTRIA							
Ueberetsch Ry.	Bozen–Mendelridge	10.7	D.C.—1,200 v.—Catenary	.....	4	.....	1910
Vienna–Pressburg Ry.	Vienna–Pressburg	43.4	D.C.—500 v.—3d rail and catenary and A.C.—1 ϕ—15,000 v. catenary.	6, D.C. 8 A.C.	10 D.C.	24 A.C.	1911
Mittenwald Ry.	Innsbruck–Scharnitz Garmisch–Partenkirchey Griessen–Reutte	66.5	A.C.—1 ϕ—15~—15,000 v.—Catenary.	9	.....	.....	1912
Austrian State Rys.	St. Pölten–Mariazell–Gusswerk	57.0	A.C.—1 ϕ—25~—6,500 v.—Catenary.	19	.....	.....	1910
NORWAY							
Thamshavn–Lökken Ry.	Thamshavn–Svorkmo–Lökken	.....	A.C.—1 ϕ—25~—6,600 v.—Catenary.	8	1	.....	1908
Norwegian State Rys.: Rjukanbanen Line	Notbdden–Tinosset	19.0	A.C.—1 ϕ—15~—10,000 v.—Catenary.	5	.....	.....	1911–12
" "	Sagheim–Vestfjorddalen *	19.6	" " " "				
	Kristinia–Drammen	.....	" " 16,000 v.—Catenary	†24	.....	.....	Under construction
	Riksgransen–Narvik	.....	" " —25~ "	†11	.....	.....	"
SWEDEN							
Swedish State Ry.	Kiruna–Riksgränsen	81	A.C.—1 ϕ—25~—16,000 v.—Catenary.	22	.....	.....	1914
	Kiruna–Gallivare	156	" " " "	.....	.....	.....	1920
	Gallivare–Ripats		" " " "	.....	.....	.....	1921
	Nattavaara–Svartön	.....	" " " "	‡12	‡2	.....	Under construction
	Riksgränsen–Narrik (Norway)	.....	" " " "	‡10	.....	.....	"
	Stockholm–Goteborg	.....	.....	.....	.....	.....	"
Roslags Ry.	Stockholm–Djursholm	.....	.....	.....	.....	.....	1893
Hälsingborg – Rää – Ramlösa Ry.	.....	.....	.....	.....	.....	.....	1906
Mellersta Oestergötland's Ry.	Borensberg–Klockrike	.....	.....	.....	.....	.....	1908
	Linköping–Fagelsta	.....	.....	.....	.....	.....	1915
	Fornasa Motala	.....	.....	.....	.....	.....	1915
Stockholm–Saltsjöbaden Ry.	.....	.....	.....	.....	.....	.....	1913
Lund–Bjärred Ry.	.....	.....	.....	.....	.....	.....	1916
Klarälv Rys.	Karlstad – Munkfors – Hagfors – Filipstad.	.....	....	.....	.....	.....	Under construction

* This section of line owned by Norsk Hydro. † To be delivered in 1921. ‡ To be delivered in 1922.

See also Table K on page 323 and Table K-2 on pages 326 and 327.

TABLE K-2

Railroad	Termini	Route, miles	System of electrification	No. of locomotives	No. of motor cars	No. of trailer cars	Date installed
			SWITZERLAND				
Bernese Alps Ry	Spiez–Frutigen	8.7	A.C.— 1 ϕ — $16\frac{2}{3}\sim$ — 15,000 v. — Catenary.				1910
(Berne–Loetschberg–Simplon.)	Frutigen–Brieg	37.3	" " " "				1913
	Spiez–Scherzligen	6.2	" " " "				1915
	Spiez–Interlaken–Boenigen	12.4	" " " "	28	3	.....	1920
	Spiez–Erlenbach–Zweisimmen	21.7	" " " "				1920
	Thun–Belp–Berne	21.1	" " " "				1920
	Berne–Schwarzenburg	13.0	" " " "				1920
Rhaetian Railways	Schols–Bevers	38.5	A.C.— 1 ϕ — $16\frac{2}{3}\sim$ — 11,000 v. — Catenary.				1913
	St. Moritz–Samaden–Pontresina						
	Bevers–Thusis	47.2	" " " "				1919
	Filisur–Davos						
	Thusis–Languart	34.8	" " " "	21	.....	.....	1921
	Davos–Klosters						
	Klosters–Landquart						
	Reichenau–Dissentis	51.6	.....	Electrification under construction.			
Swiss Federal Rys	Scherzligen–Thun	.6	A.C.— 1 ϕ — $16\frac{2}{3}\sim$ — 15,000 v. — Caternary.	4	.....	.....	1918
	Berne–Thun	19.3	" " " "				1919
	Erstfeld–Biasca	55.9	" " " "	59	.....	.....	1920
	Biasca–Chiasso	46.6	" " " "				
	Immensee–Rothkreuz	4.3	" " " "				
	Erstfeld–Lucerne	37.3	" " " "	10	Electrification under construct'n		
	Goldau–Zurich	27.8	" " " "				
	Lucerne–Zug	17.4	" " " "				
	Sion–Lausanne	57.2	" " " "	11	"	"	
Burgdorf Thun Ry	Burgdorf–Thun–Langnau	34.8	A.C.— 3 ϕ — 40$\sim$ — 750 v.— Catenary.	5	6	14	1899
Simplon Tunnel Ry	Sion–Brieg–Iselle	47.2	A.C. 3 ϕ — $16\frac{2}{3}\sim$ — 3,000 v.— Catenary.	4	.....	.....	1905
Rhatische Ry	St. Moritz–Schuls	.....	A.C.— 1 ϕ 10,000 v.— Catenary	14	.....	.....	1913
	Samaden–Pontresina						
Fribourg–Morat–Anet Ry	Fribourg–Morat–Anet (Ins.)	20.5	D.C.— 840 v.— 3d rail	.....	.....	.....	1903

TABLE K-2 (Continued)

HOLLAND							
Netherland Railways	Rotterdam-the-Hague-Scheveningen	21.7	A.C.—1 ϕ — 25~ — 10,000 v.—Catenary.	.....	78	17	1908
ITALY							
Italian State Rys	Milan Varese-Porto Ceresio	45.2	D.C.—650 v.—3d rail	.....	.....	.....	1901
	Valtellina Lines						
	Lecco-Colico-Sondrio	49.3	A.C.—3 ϕ — 15 to 16~ — 3,400 v.—Catenary.	15	.....	.....	1901
	Colico-Chiavenna	16.3	" " " "				1901
	Monza-Lecco	23.2	" " " "				1901
	Turin-Bussolena-Modane	64.9	A.C.—3 ϕ — 16 to 17~ — 3,700 v.—Catenary.	.....	.....	.....	1919
	Bussoleno-Susa	4.7	" " " "	.....	.....	.....	1919
	Turin-Pinerolo	23.0	" " " "	.....	.....	.....	1917
Italian State Rys	Savona-San Giuseppe-Ceva	28.9	" " " "	.....	.....	.....	.....
	Savona-Sampierdarena	24.8	" " " "	.....	.....	.....	1916
	Giovi Lines						
	Ronco - Busalla - Sampierdarena	16.9	" " " "	40	.....	.....	1916
	Ronco - Mignanego - Sampierdarena-Genoa	19.7	" " " "				1910 1914
	Genoa-Pisa	.....	.....	.....	.....	.....	Under construction.
	Bologno-Pistoia-Florence	.....	.....	.....	.....	.....	"
	Bologno-Faenza-Florence	.....	.....	.....	.....	.....	"
	Pinerolo-Torre Pellice	.....	.....	.....	.....	.....	"
	Bricherasio-Barge	....	.....	.....	.....	.....	"
	Rome-Tivoli	.....	.....	.....	.....	.....	"
	Rome-Carano-Nettuno	.....	.....	.....	.....	.....	"
	Voghera-Alessandria	.....	.....	.....	.....	.....	"
	Tortona-Nova	.....	.....	.....	.....	.....	"
	Tortona-Arquata	.....	.....	.....	.....	.....	"
Ferrovia-Biella Co. Limited	Santhia-Biella	18.6	D.C.—4,000 v.—Catenary	.....	.....	.....	.....
Ferrovie-Torino-Cirie-Lanzo Co. Limited.	Turino-Lanzo	13.4	" " "	.....	.....	.....	1921
Valle Brembana Electric Railway Co. Limited.	Bergamo-San Giovanni in Bianco	18.8	A.C.—1 ϕ — 25~ — 6,000 v.—Catenary.	.....	.....	.....	.....
Mediterranean Ry. Co	Terni-Umbertide	06.9	A.C.—1 ϕ — 25~ — 11,000 v.—Catenary.	.....	.....	.....	.....
	Ponte San-Giovanni-Perugio	3.3	" " " "	.....	.....	.....	.....

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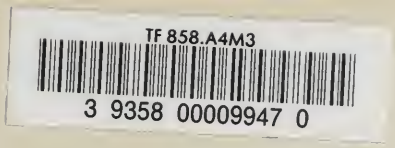

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